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# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE



AGARD ADVISORY REPORT 314

## Flight Mechanics Panel Working Group 19 on

# Operational Agility

## (La Maniabilité Opérationnelle)

*This Advisory Report has been prepared at the request of the Flight Mechanics Panel of AGARD.*



NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization

*Organisation du Traité de l'Atlantique Nord*

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According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;
- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Exchange of scientific and technical information;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

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# Preface

Flying characteristics and flying qualities have been, for many years, major interests of the Flight Mechanics Panel of AGARD and a Panel Sub-Committee was formed to specifically address this area. Following recommendations by this Sub-Committee, the Flight Mechanics Panel sponsored Working Group 17 which, from 1987–1990, examined "The Handling Qualities of Unstable, Highly Augmented Aircraft" and then organised a Symposium on "Flying Qualities" in autumn 1990.

Stemming from these activities, it was recognised that flying qualities and traditional aircraft performance parameters did not characterise the capability or effectiveness of combat aircraft, although they do offer a guide. Other expert groups had reached a similar conclusion. The subject that arose from these realisations was "agility". Recognising that this was an incomplete or immature concept and that a wide variety of sometimes disparate views existed, the Panel formed a further Working Group, WG 19, consisting of specialists from the AGARD member countries, to study the subject under the title of, as originally proposed, "Functional Agility" or as now preferred by the members of WG 19, "Operational Agility".

The specific aims of the Working Group were:

1 To provide definitions, which are universally acceptable, of the terminologies involved in agility.

2 To collate the results of lessons learned from experiments on agility.

3 To define metrics or figures of merit for use in design and evaluation.

4 To explore and document the theoretical foundations.

5 To explore the operational pay-off of balanced capabilities between the airframe, systems and weapons.

6 To highlight any specialised aspects applicable to rotorcraft.

7 To indicate possible means of evaluation in flight.

8 To recommend areas for further research and development activities, including possible collaborative projects.

Five working sessions were held at places of special interest to the group, between 1991 and 1993.
Venues were:

Edwards AFB, Lancaster, California, United States
STPA, Paris, France
Sikorsky Aircraft, Stratford, Connecticut, United States
Aermacchi, Varese, Italy
British Aerospace, Warton, United Kingdom.

The final report was very much a team effort and consists of contributions from all members of the Working Group. AGARD acknowledges the contributions made in experience, knowledge, time and effort in the preparation of this document by a team of competent engineers.

Keith McKay
Member, AGARD Flight Mechanics Panel
Chairman, AGARD Working Group 19

# Préface

Les caractéristiques et les qualités de vol sont des sujets qui suscitent un grand intérêt de la part du Panel AGARD de la mécanique du vol depuis de nombreuses années. Un sous comité du Panel a spécifiquement été créé pour étudier ce domaine Suite aux recommandations formulées par ce comité, le Panel de la mécanique du vol a créé le groupe de travail No. 17 qui s'est penché sur la question des "Caractéristiques de manoeuvrabilité des aéronefs à stabilité fortement augmentée" de 1987 à 1990, pour ensuite organiser un symposium sur "les qualités de vol" en automne 1990.

Grâce à ces activités, il a été admis que les qualités de vol et les paramètres classiques des performances des aéronefs traditionnels ne suffisaient pas pour caractériser les capacités et l'efficacité des avions de combat, bien qu'ils puissent servir de guide. D'autres groupes d'experts étaient arrivés à des conclusions similaires. Le sujet qui s'est finalement dégagé de ses délibérations a été la "maniabilite". Le Panel, constatant qu'il s'agissait d'un concept incomplet et prématuré, et qu'il existait une grande diversité d'opinions sur ce sujet, a créé un deuxième groupe de travail, le WG 19, composé de spécialistes des différents pays membres de l'AGARD afin d'étudier le sujet tel qu'il avait été définit à l'origine, c'est à dire sous le nom de soit "la maniabilité fonctionnelle", soit "la maniabilité opérationnelle" selon les dernières préférences exprimées par les membres du WG19.

Les objectifs spécifiques du groupe de travail furent les suivants:

1 fournir des définitions, qui soient universellement acceptables, de la terminologie utilisée dans le domaine de la maniabilité

2 rassembler les resultats et les enseignements tirés des expériences faites dans le domaine de la maniabilité

3 définir la métrique ou les facteurs de mérite à retenir pour la conception et l'évaluation

4 étudier et documenter les fondements théoriques

5 apprécier la rentabilité opérationnelle de l'harmonisation des capacités cellule, systèmes et armes

6 signaler d'éventuels aspects spécifiques aux aéronefs à voilure tournante

7 indiquer les possibilités d'évaluation en vol

8 faire des recommandations concernant les domaines où les activités de recherche et développement devraient s'amplifier à l'avenir, y compris d'éventuels projets de coopération.

Cinq séances de travail ont été organisées entre 1991 et 1993, dans des lieux ayant un intérêt particulier pour le groupe, à savoir:

Edwards AFB, Lancaster, California, Etats-Unis
STPA, Paris, France
Sikorsky Aircraft, Stratford, Connecticut, Etats-Unis
Aermacchi, Varese, Italie
British Aerospace, Warton, Royaume-Uni

Le rapport final est le fruit d'un véritable travail d'équipe, puisqu'il est composé de contributions de touts les membres du groupe de travail. L'AGARD tient à exprimer sa reconnaissance vis à vis de l'expérience, des connaissances, du temps et des efforts consentis par une équipe d'ingénieurs compétents, pour la rédaction de ce document.

Keith McKay
Member, AGARD Flight Mechanics Panel
Chairman, AGARD Working Group 19

# AGARD Working Group 19 Membership

| | |
|---|---|
| **Canada** | Captain A.Z. Reif, Canadian Air Force |
| **France** | Mr R. Jouty, STPA |
| **Germany** | Hr H. Galleithner, DLR<br>Hr D. Hartung, Deutsche Aerospace |
| **Italy** | Sig R. Bava, Alenia<br>Sig U. Gianchecchi, Aermacchi<br>Lt Col. G. Fristachi, Italian Air Force<br>Prof. M. Innocenti, Auburn University/University of Pisa |
| **United Kingdom** | Mr P. Gordon-Johnson, British Aerospace<br>Dr G.D. Padfield, Defence Research Agency<br>Mr K. McKay, British Aerospace |
| **United States** | Col. R.A. Borowski, USAF/Lockheed Engineering Sciences Co.<br>Mr J. Hodgkinson, McDonnell-Douglas<br>Mr N. Lappos, Sikorsky Aircraft<br>Mr A. Skow, Eidetics |

Thanks are also due to the following:

Dr U. Lynch, Eidetics
Captain J. Beck, USAF

who contributed their time and effort to the work and final report of the group.

# Foreword

*The fighter pilots have to rove in the area allotted to them in any way they like, and when they spot an enemy they attack and shoot him down; anything else is rubbish.*

*Baron Manfred von Richthofen*

Changing technology and a changing world situation have affected the environment of the fighter pilot. In a bipolar world, friend and foe were easily distinguished. Before stealth, radar provided a reliable warning that an engagement might be imminent. In most battle theaters, ground or air-based guidance set up engagements so a pilot could enter from a position of advantage or at least from a known intercept geometry. Although Baron von Richthofen's guidance from World War I remains applicable, many of the other maxims by which fighter pilots have operated, have become obsolete. If the future can be predicted from the immediate past, fighter pilots should expect continued profound change. Technology's rate of advancement will be matched by the rate of geopolitical change.

It is easy to prescribe a process for dealing with change, but exceptionally hard to execute the process. Success requires one to anticipate, react, re-evaluate and modify tactics. After settling on a course of action, one must be ready to change direction quickly if circumstances dictate. One must make every effort to perceive rather than avoid the need for change. One must recognize the normal human tendency to avoid change. This approach, whether applied to fighter airplanes or any other field of human endeavor, translates to agility.

Even a program for reacting quickly can result in a narrowing of horizons. Especially in today's technology environment, approaches and concepts that worked yesterday can be less successful today, or worse irrelevant.

A quick survey of fighter attributes through the jet era is instructive. In Korea, maneuverability proved foremost. Airplanes with powered control systems were able to maneuver at high-speed flight conditions that nearly froze the controls of other airplanes. The best airplanes of the era are still considered models of agility and superior handling qualities. After Korea, heat-seeking missiles and then radars and radar-guided missiles gradually became more dominant. Perhaps it was reliance on these systems as well as larger flight envelopes that led to less emphasis on precise aircraft control. Long after the advocates of beyond visual range systems pronounced air-to-air combat as the territory of the long-range missile, Desert Storm proved that the long-range missile could indeed dominate air-to-air combat. But the next change in direction is already clear. Stealthy fighters are in development and radar-seeking missiles are within the grasp of technology. As with long-range radar missiles, these will likely not meet initial promises, but then will suddenly become dominant factors. The critical regime of air-to-air combat may very well again become within visual range, but now at very high speeds and closure velocities. In spite of reduced signatures, breaking off combat will continue to be difficult because of weapons characteristics. Getting out ahead of the implications of this latest design revolution without opening a new aspect of vulnerability was much on the mind of the Working Group during its activities.

Recognizing that the guidance developed by the Working Group should survive at least this predictable change in technology, we defined our subject, Operational Agility, as a full-system capability rather than a special set of flying qualities or a capability to maneuver at extreme angles of attack. We feel strongly that it makes little sense to design airplanes to fly at high angular rates if the sensors cannot track at those rates or if weapons cannot function. Operations at high g, high speed, or any other extreme of the operational envelope require similar considerations. Recovery from operations at extremes of the envelope is at least as important as the ability to operate in those extremes. Tradeoffs between agility contained in the aircraft's flight envelope, in the missile's capability and in various on board and external electronic systems must be made using a rational evaluation technique.

Finally, the Working Group wanted to find a way to affect systems delivered to the military services. We feel it is important to provide a context in which operational people can set requirements that translate to engineering parameters and that analysis, simulation and flight test should be able to validate that those parameters have indeed been met. The common tie, we believe, is a set of mutually understood specifications. The specification set must be broad enough to include all aspects of system performance and to allow trades between those aspects to be made by the designers.

We in the Working Group believe the process of our deliberations is as important as the product of them. Individually, we each emerged with a broader understanding of our subject and of individual and national approaches to the subject.

# Contents

## Summary

The environment in which a fighter pilot is required to operate is subject to continual change. This change arises from advances in technology and the altering world political situation. The only prediction that can be made with any confidence is that this change process is bound to continue with an unpredictable rate.

In dealing with change, it is easy to prescibe a process but extremely difficult to implement the process with success. Success requires anticipation, reaction, re-evaluation and modification of tactics and processes. The need for change must be recognised and accommodated. Such an approach, whether applied to fighter airplanes or any field of human endeavour translates to agility.

The Flight Mechanics Panel of AGARD has sponsored this Working Group to investigate the topic of agility as it applies to military combat aircraft. In undertaking this work, the Group encountered many definitions of agility, some of which represented widely differing viewpoints. Often, in the past, protagonists of the varying ideas have fallen into heated arguments as to who is right. From our deliberations and discussions, the answer has emerged that no-one was wrong, that all were right, at least in part. However, few had taken the time to stand back and take an all embracing view. Had they done so, then the message that all were trying to put forward might have had a wider and more sympathetic audience.

Fortunately, within the Group, we have been able to stand back and examine the arguments with a dispassionate approach which has enabled us to understand the various arguments and see the common ground, rather than the differences.

All of the agility concepts that have been put forward have some merit. What was required was a way to relate the ideas and be able to apply them in a manner that is both reasonable and logical from both the viewpoints of the designer/supplier of aircraft and the customer/user of the vehicles that result.

In defining a Weapon System, it is essential to examine the component parts and their interaction, whether this be airframe, propulsion system, sensors, cockpit and avionics or the weapons themselves and establish a balance and synergistic integration between all of the components appropriate to the intended role and missions of the aircraft. It is the need to achieve balance and integration that is the prime driver for understanding Operational Agility as a set of concepts, supported by metrics which fit into a generalisable framework, capable of evaluating a complex combat aircraft design with a view to maximising the effectiveness of that design within affordable cost limits.

This points the way forward for future aircraft. Achievement of this design balance requires all of the Weapon System attributes to be studied, evaluated and weighed against each other, together with the cost implications, to determine the optimum solutions. This may imply significant compromises if the roles and perceived threats are too diverse. A consequence is that future design specifications and requirements will need to be prepared in a different way from that traditionally used, in order that the correct design balance for a given set of applications can be achieved. Specifications will need to concentrate on the functional roles, the perceived threats and, hence, derive the the detail engineering requirements once the balance has been established.

With regard to the agility of a Weapon System, there are still some questions to which answers are elusive. It is not clear what the upper bounds are determined by. Frequently, it is assumed that more must be better, but this may not be so if a balanced design is to result. A better question which should be asked when specifying new Weapon Systems, or developments of existing ones, is "How much is enough?" This will place a greater emphasis on the conceptual stage of design, but to the benefit of the overall sustem development programme.

This report examines the subject of Operational Agility with a view to providing the reader with sufficient background to follow the concepts which have evolved together with the methodology and metric framework which resulted from the activities of the Working Group. This framework has its origins in the Flight Mechanics disciplines, where most of the previous workers in this field have made their efforts, but it was soon realised that the concepts could very quickly be extended to apply to all areas of combat aircraft design. It is in these other areas that most work remains to be undertaken to establish the detail of the appropriate metrics. It is also suggested that the methods and concepts can be applied to any air vehicle, in a similar manner to Handling Qualities, where the design criteria have evolved for a number of classes of aircraft, including transports. Each class has a need for its "agility" to be recognised and identified.

For convenience, this report has been written in such a way that it can be read either as a total document or as a series of stand-alone papers. To facilitate this, each Chapter or Section is self-contained, with its own conclusions and recommendations.

In developing the subject of Operational Agility a set of definitions has been arrived at which are consistent with the proposed methodology for evalation and specification of the aircraft and its associated onboard systems. These definitions are:-

> ***Operational Agility - the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.***
>
> ***Transient Agility*** is a continuously defined property reflecting the instantaneous state of the system under consideration.
>
> ***Airframe Agility*** - the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.
>
> ***Systems Agility*** - the ability to rapidly change mission fu .tions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.
>
> ***Weapons Agility*** - the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures.

The scope of the report covers the airframe, the systems and weapons, the pilot-vehicle interface and evaluation methodologies and techniques. It retains these definitions as a basis throughout, providing examples when this has been possible, from the experience available to the Working Group. Each Chapter, where appropriate, highlights the lessons which have been learned and where further work will be required to complete the picture.

A methodology has been derived for assessment of the various component systems which contribute to the Operational Agility or combat effectiveness of a Weapon System. This methodology is described initially in Chapter 2.2, where it has been derived from consideration of the Airframe Flight Mechanics. However, it is sugges :d, with some evidence to support the assertion, that the framework will also apply to any system which contributes to the Operational Agility. Further, it allows the relative worth of the differing systems to be evaluated against each other.

Perhaps more significantly, it is apparent that the concepts of Agility apply to all classes of aircraft, not just to combat designs, in a similar manner to Handling Qualities. As an example, the case of a helicopter landing on a moving deck at sea requires Operational Agility, but in a different way to combat. Other examples could readily be brought to mind. With further work, it would be possible to derive the appropriate measures to apply to these classes. The concepts presented in this report will assist in the process of developmentof the appropriate criteria and metrics.

The nal Chapter, dealing with Evaluation, highlights the role of evaluation in the design and procurement of highly agile aircraft systems. Evaluation forms an essential element of the process of understanding Operational Agility. This should start at the conceptual stage and continue throughout design and flight test, including early Service assessment, operational assessment and training. The methodology and concepts discussed enable the tools appropriate to each stage of the activity to be decided upon.

From the work of the Group, a number of major conclusions have been reached; these are summarised below:-

***1)*** ***There is a mismatch between the Weapons and the Airframe capabilities.***

A great deal of effort has been expended in developing the airframes to be highly agile but this has not necessarily been matched by the equivalent development of the weapons that the airframes carry. This does

not imply that there has been no activity, there has, but there needs to be a concurrency in the development if the total effectiveness is to be maximised.

2) ***The way in which aircraft and their associated systems are specified is in need of review and revision.***

Current combat aircraft specifications and requirements are not really appropriate for the complex, integrated vehicles which have to result from attempting to meet the requirements. The very complexity of the vehicles often means that decisions relating to the design options may not take into account all the influences, leading to engineering difficulties and expense later in the processes of development and procurement.

The concepts and proposed evaluation methodology involved in Operational Agility can assist in the process of determining what the specification and requirements should contain and in the design and subsequent evaluation of the vehicle that results.The object should be to define the function and purpose, then establish the methodology and means of evaluation prior to issue of detail engineering design specifications. To achieve this, there needs to be close interface and teaming between the customer, end user and possible designers and suppliers of equipment, airframes, etc.

3) ***The achievement of a cost effective design balance and the maximisation of Weapon System combat effectiveness are central to the concepts of Operational Agility.***

There has been a problem of vocabulary which has inhibited communication in this field. However, this report should assist by providing the necessary definitions of agility terminology by which the communication can be established. The key is to recognise the broad scope that Operational Agility encompasses, and to be specific about which aspect or system is being discussed.

To achieve the design balance not only needs the definitions of agility, it also requires standardised agility figures of merit, together with a proven quantification methodology applicable from concept through design, test and into operational contexts. The role for the vehicle will give rise to differing weighting factors for the agility attributes, influencing the design balance.

The proposed metrics structure seems to logically characterise the airframe agility, ie. transient, experimental and operational. As yet, there is insufficient data at present to clearly determine the tactical meaning of airframe agility metric results.

The Operational Agility structure is applicable to mission oriented and weapons agility.

4) ***There is a need for Global data acquistion.***

In order to understand and quantify the Operational Agility of a Weapon System, there is a need to gather data on all the systems simultaneously, in order to determine the actual usage that is being made of all the systems at any time. Additionally, there is a need to record data under realistic operating conditions, including combat use and even actual war. The capability exists now to gather the information and to handle the database that results. The implication is that the data acquistion would need to be structured with all the potential users in mind and should be sufficiently flexible to accommodate changing and growing needs.

5) ***Combat success requires more that an agile airframe.***

Use of the proposed Operational Agility methodology should enable the crucial aspects of each contributing system to be identified. The object will be to focus on the time delay of each aircraft subsystem with the aim of reducing the delays without over-emphasis on a specfic system aspect which could potentially lead to increases in time delays by other components, including the pilot.

Clear understanding the time delays for mission functions enables identification of actions to automate, ie housekeeping, leaving the crews limited attention time to more critical tasks such as the tactical situation.

*6)* ***Quickness parameters provide best means to bound agility.***

One of the concerns which has been raised during the work of the Group relates to whether or not there is an upper limit to agility, whether this be the airframe or any other system. This is perhaps most readily understood in terms of the airframe agility. Some of the upper limits are comparatively easy to describe, as they result from the limitations of the structure or rate at which controls move.

However, there are concerns that very high performance may be dangerous to use, as the more aggressive the use of the airframe, then the more the handling qualities may degrade. In very high workload situations, this may result in unsafe characteristics but the situation is likely to be difficult to quantify as it will depend on the aggressiveness of the pilot. If high performance is dangerous to use, then pilots will avoid using it, hence flying qualities can provide major restrictions on the agility of a particular airframe.

The concepts of quickness parameters are comparatively well developed for rotary wing vehicles, as exemplified by ADS33C. For fixed wing, the concept is still in its infancy, but it would appear to be well worthwhile developing as an analysis tool, particularly if the vehicle will have to demonstrate high levels of agility in its class. Flying qualities need to be considered in the early design process. The concept of an "agility factor" for this phase of work where the focus is on probability of mission success or failure combined with a mission task element method of analysis will assist in mission effectiveness trade studies

*7)* ***Airframe agility is designed in from the outset. Only in exceptional circumstances can it be added later, implying the basic design was not balanced properly.***

Operational Agility concepts can and should be applied at the outset of the design process, starting even with the Operational Analysis work. The objective is to determine the correct design balance between airframe aspects, weapons and the onboard systems with a view to maximising the operational effectiveness at an affordable cost and to ensure that there is adequate growth potential in the aircraft to take it through its Service life.

Typically, combat aircraft have to remain in Service for around 20 to 25 years. During this time, the onboard systems can be upgraded many times, as the changing needs of the operational environments dictate. However, the airframe is much harder to make any fundamental changes to, implying that the flexibility has to be built in at the outset. Provided this is recognised early in the design process, before detail work starts, then it is more easily accommodated. Adding capability later is always more expensive, and may need major structural repair work.

*8)* ***Rapid prototyping of crew stations is an agility enabler.***

Modern crew station design focusses on the tasks for the specific missions which are to be performed. The objective is to be more effective in an overall performance sense and to be able to respond to changes in the external environment more adeptly than at present. This requires an understanding as to how the crew interface with the systems in order that the appropriate displays of information, as opposed to data, can be implemented. The process can and should be used to decide which functions are to be automated, rather than what can be automated.

*9)* ***Changing combat situations result in dynamic missile envelope conditions that press the ability of the mission systems to present up-to-date information.***

The key here is the need for the systems to display information, not data, but in a form that the pilot can readily relate to and with a speed that is commensurate with the changing situation. Under some circumstances, it may even be appropriate for the system to take action and then inform the crew that it has already dealt with a situation, for example in response to an external threat. Again, rapid prototyping alloyed to adequate simulation and evaluation will prove to be key enablers of such technology.

10) ***Pilot-Vehicle Integration for the expanded flight envelopes provides a major challenge with regard to displays.***

When at high angles of attack, new forms of displays are required to ensure that awareness of the flight path vector is maintained. Recovery from high angle of attack manoeuvres, using $45^{\circ}$ or more is accompanied by the feeling that the aircraft is not reducing angle of attack initially. They appear to maintain AoA and reduce flight path angle. This places additional burden on developing means to inform the pilot as to what is happening, particularly if the correct things are taking place, but it does not feel natural.

11) ***Integration of propulsion systems into agile airframes places special requirements on the propulsion unit and its integration into the design.***

Engine response times need improving for carefree handling. The goal should be to obtain maximum power on the same time as the pilot can achieve his desired AoA.

Thrust vectoring offers a powerful control effector. A careful cost/benefit analysis is required for each individual project study. It may not always be beneficial or necessary to include such technology to achieve the desired effectiveness. PST should not be considered if it drives the configuration such that it penalises the aircraft over the rest of its design flight envelope.

12) ***The study of Operational Agility is still immature.***

On the limited evidence available to the Working Group, the concepts of Operational Agility do appear to be valid and examples have been provided in the report. However, the concept of Sub-system agility requires the development of a suitable vocabulary and unification of existing work. The definitions derived by the Group could provide a basis for further work in this area, which would appear to offer a worthwhile reward in terms of the operational effectiveness enhancements that could result.

There are also a number of recommendations which follow from the conclusions, as follows:-

1) **The Mismatch of Missiles and Weapons with Airframes.**

There is need for some form of formal discussion relating to the mismatches in development of missiles, or weapons in general, and airframes. The Group believes that this could best be addressed by a Symposium to illustrate the current problems and identify possible ways forward. It is noted that such an activity could relate or be a part of the proposal for a Symposium on Weapon System Integration.

2) **The Need for a Database Relating to the Systems Use in Operations**

There is a need for data to be obtained from service which can be made available to the whole community involved in aircraft design, assessment and operation. The capability to provide the necessary information exists and to handle the database that results. The Group recommend that a new working group could usefully address the problem, with a view to providing the necessary database. This new group would need the services of experts in operational use, design, and information systems technology. The objective would be to recommend ways of achieving a database of use to all disciplines involved in the design and procurement of Operationally Agile aircraft.

3) **The Tactical Meaning of Agility Metrics needs to be Established**

Work needs to be undertaken to establish the tactical meaning of agility metric results, such that the value of Operational Agility studies can be quickly established and the resulting designs be shown to be more effective in a manner which fits the needs of the operators and purchasers.

4) **Additional Studies of Agility Metrics and the Upper Limits of Agility.**

Further studies are recommended in the following areas before a complete understanding of Operational Agility will be quantified, viz:-

Sub-System agility concepts and the possible metrics need to be developed further with more examples of application of the proposed structure to test its fitness.

Develop more rotary wing metrics compatible with the Operational Agility structure, particularly for the airframe, which currently lags the work done in the fixed wing areas.

Develop a complete library of mission task elements which can be used in the development and assessment of Operational Agility for either fixed or rotary wing vehicles.

As the upper bounds on agility remain to be determined, there is a need to gather more quickness parameter data. At present, the quickness parameter concepts are used by the rotary wing community, but it would appear applicable and useful for fixed wing applications as well. It is recommended that further work be done on this concept for fixed wing application.

Further analysis of the relation of flying qualities and vehicle performance to define the upper limits on airframe agility is needed, particularly if aggressive use of the airframe causes the handling qualities to degrade. This requires dedicated evaluation tasks where both the objectives and success criteria are clearly defined.

Develop an "aggressiveness" rating system to parallel Cooper-Harper.

5) **Establish the Influences on Awareness of High Rate and Acceleration Manoeuvres.**

The effect of high angular and linear rates and accelerations under varying visual reference conditions needs to be established if agile airframes and displays with which the pilot can interface correctly are to be achieved. The concern here is that rates and accelerations which might be perfectly acceptable during preplanned or anticipated manoeuvres will be of little use or even dangerous when manoeuvring aggressively, particularly in a dynamic combat environment.

6) **Establish the Influence of Prolonged Exposure to Sustained 'g' at Moderate Levels.**

Determination of the relationship between sustained high 'g' below the level causing loss of conciousness and loss of situational awareness. This is a direct corollary of the previous recommendation.

7) **Revise the Way in Which Future Aircraft Specifications are Written.**

Specifications should be written to define the function to be achieved, from which the levels of performance can be derived in conjunction with the appropriate trade studies. Each new airframe project should be assessed in its own right to establish which technologies are affordable or relevant. Technology should not be included for its own sake. No one item should be inviolate, all items in the detail engineering specification should be tradeable to ensure the correct design balance results.

8) **Adopt Concurrent Engineering Methods.**

A concurrent engineering approach between customer and supplier will help to ensure that the necessary objectives are achieved.

The Group's view is that the study of Operational Agility is in a similar situation to that seen by the Flying Qualities community some twenty years or more ago when faced with fly-by-wire, highly augmented airframes for the first time. Much remains to be accomplished before Operational Agility attains the same status as Flying Qualities currently has. However, the benefits which should accrue from better understanding of Operational Agility will encourage a rapid progression. In particular, when funds are resticted, it is essential that there is an adequate

understanding of where funds are best targetted for any project. The Operational Agility methodology derived by the Group should be able to provide major assistance to making logical decisions.

It has become clear that additional work is required in a number of areas, especially relating to the avionics, sensors and cockpit design aspects or pilot vehicle interface.

Finally, it is considered that the Group has met the objectives which were set out for and that this report summarises the understanding which has resulted from the activities. The subject of Operational Agility is at a stage similar to that of Handling Qualities some 20 years ago.

There is still much to do and understand. The driver will remain effective combat aircraft at a cost affordable to the customer.

## Chapter 1: Specifying Operational Agility for Combat Effectiveness

### 1.1 Introduction

#### 1.1.1 The Background to Operational Agility

The environment in which a fighter pilot operates is subject to continual change due to technology advances and the altering world situation. The only prediction which can be made with confidence is that profound change should continue to be expected.

To understand the background to Operational Agility it is worth considering some of the historical background to agility.

The first air to air conflicts occurred in the Great War. Here, aircraft were, for the most part marginal with regard to performance, stability and controllability. Indeed, many combat losses could be attributed to these shortcomings rather than the action of the enemy. However, some of the aircraft were regarded, and still are, as models of the agile fighter, particularly in the hands of an expert pilot, or "ace". The basic skills required were the ability to remain in control and shoot accurately.

For subsequent conflicts, the same basic skills were required, although airframes were better stabilised and controlled and had increased power available, resulting in higher speeds. With radar and radio, it became possible to receive guidance towards the targets that the ground control perceived as the prime threat. Weapons remained visual range, however, but regardless of this, the increased speeds and the added information changed the difficulty of the pilot's task due to the implications on his situational awareness and choice of tactics. Increasingly, the combat results became more clouded by the interaction of the systems available to the pilot and his ability to assimilate the information provided.

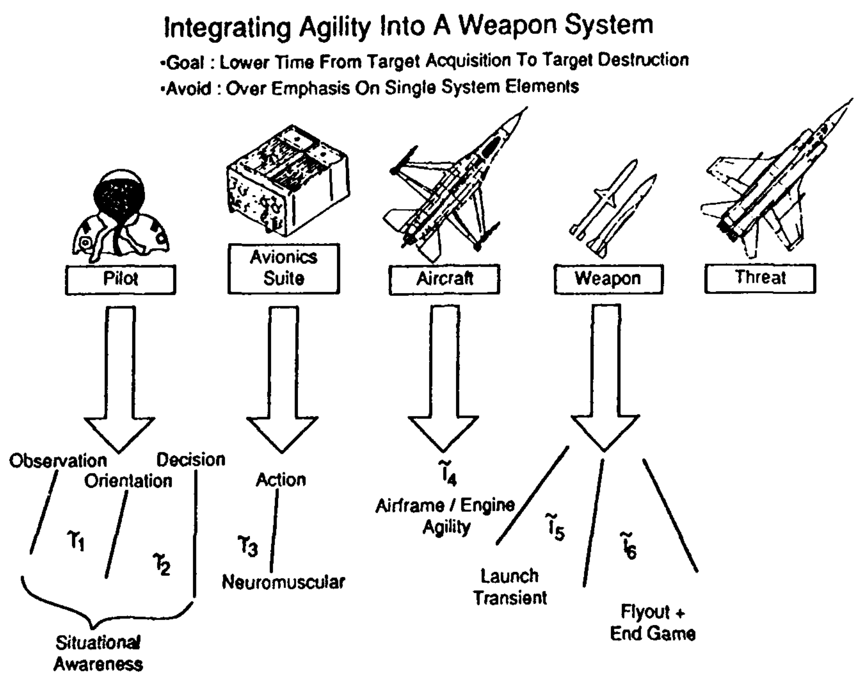
The advent of jets, airborne radar capability, missiles and counter offensive equipment have all tended to complicate the picture whilst attempting to improve the ability to perform the same basic tasks, ie. finding the opposition and shooting him down. Korea demonstrated the benefits of high performance combined with good handling, to the detriment of the Communist forces. However, some lessons were forgotten, and had to be relearned in later conflicts.

A classic modern example derives from the Falklands conflict, where the Sea Harrier had significantly less performance than the opposing Mirage and Dagger aircraft, but was able to acquit itself very successfully because of its radar, weapons, the back-up of ship-borne control radars and information and not having to operate at the extremes of its range. Further examples come from the USAF and USN aggressor training schools, where the success of the F-5 in the hands of very skilled, combat experienced pilots caused a number of upsets in training combats against apparently more capable opponents.

As a direct consequence, over recent years, there has been a growing recognition that studying traditional performance parameters and Flying Qualities does not adequately characterise the differences between aircraft or their relative effectiveness. Considerably more is involved in understanding what makes an aircraft effective and many workers have been attempting to qualify what the extra something is and quantify its measurement. The studies of agility are a direct result.

The Working Group has defined, therefore, our subject of "Operational Agility" as a full system capability, including the sensors and other onboard electronic systems and the weapons. Systems which are not onboard to which the aircraft systems must relate have not been considered, specifically. Figure 1.1, taken from reference 1, illustrates the interaction of the systems in terms of the time constants which they add to the overall task, in this case of detecting the target, taking some decision and action, to destroying the target and escaping and gives clues as to how the contributions can be quantified.

**Figure 1.1: Weapon System Agility Concept**




The study of "Operational Agility" has three prime aims:-

- The design of more capable and cost effective combat aircraft.
- To present a meaningful picture of combat capability.
- To develop a metric methology for use in aircraft specification, comparison, design and evaluation.

***Operational Agility*** is defined as ***the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.*** Operational Agility provides the "big picture", in that it relates to the overall combat effectiveness of the airborne Weapon System.

### 1.1.2 Specifications and Requirements

Current air vehicle specifications and requirements are usually couched in terms which a design organisation can unravel but which do not allow the customer to form a real picture of the combat effectiveness of the overall weapon system. Significant deficiencies in "fighting qualities" may remain hidden during design and even in flight test, only emerging when a pilot in a Service attempts to deal with an apparently less capable opponent at least according to paper assessments.

Traditional energy manoeuvrability theory remains valid but it is clearly incomplete in that it fails to identify the reason or reasons for sometimes surprising failures in combat effectiveness.

To date agility has been primarily associated with the time required to change the manoeuvre state and, as such, has tended to be restricted to the engine and airframe aspects.

Clearly, there is a need for something more if such surprises are to be avoided in (mock) combat and the vehicle effectiveness enhanced. The concept of "Operational Agility" is a natural consequence as it relates to the function of the vehicle, or its combat effectiveness.

### 1.1.3 Working Group 19's Aims

The aims of Working Group 19 were defined by the Flight Mechanics Panel of AGARD and can be summarised as follows:-

1) To provide definitions, which are universally acceptable, of the terminologies involved in agility.

2) To collate the results of lessons learned from experiments on agility.

3) To define metrics or figures of merit for use in design and evaluation.

4) To explore and document the theoretical foundations.

5) To explore the operational pay-off of balanced capabilities between the airframe, systems and weapons.

6) To highlight any specialised aspects applicable to rotorcraft.

7) To indicate possible means of evaluation in flight.

8) To recommend areas for further research and development activities, including possible collaborative projects.

In order to address these aims the Group realised that it would have to go further than was perhaps originally intended and spend more time considering the concepts involved, how these might be developed into a framework suitable for detailed analysis and how evaluation could be implemented. As a consequence, the Group has addressed:-

- Development of the concept of "Operational Agility" as a means of analysing the agility or effectiveness contributions of the elements of the Weapon System: specifically these include Pilot-Vehicle Interface, Airframe and Engines, Avionics, Sensors, Control System and Weapons and their associated management.

- Provision of a framework for this analysis, indicating the possible metrics which may assist in the analysis, capable of addressing each phase of the evaluation procedure from paper concept through to flight trials.

- Highlighting the need for future Weapon System specifications and requirements to be task oriented in order to generate a picture of the combat effectiveness and capability of the vehicle.

- Indicating the areas where further work would most profitably be concentrated, including the possibility of collaborative efforts.

### 1.1.4 Future Specifications and Requirements

Current combat aircraft specifications and requirements are not really appropriate for the complex, integrated vehicles which have to result from attempting to meet the requirements. The very complexity of the vehicles often means that decisions relating to the design options may not take into account all the influences, leading to engineering difficulties and expense later in the processes of development and procurement.

There is a need to change the way in which future Weapon Systems are formulated and the concepts involved in Operational Agility can assist in the process of determining what the specification and requirements should contain and in the design and subsequent evaluation of the vehicle that results.

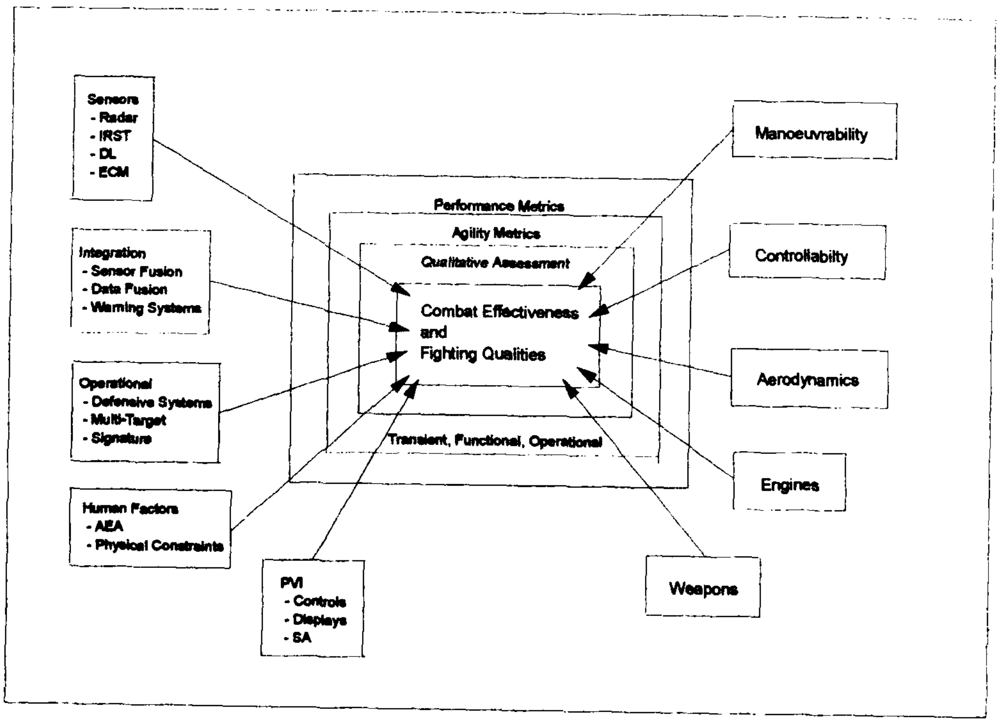
This report will develop the concepts of Operational Agility, indicating the methods which might be appropriate to evaluating the options, or at least providing assistance in understanding the choices that are available.

## 1.2 The Weapon System Design Balance

### 1.2.1 The Contributing Parts of a Weapon System

In defining a Weapon System, it is essential to consider the component parts, whether this be the airframe, including the propulsion system, the sensors, the cockpit, the avionics systems or the weapons themselves and to achieve the necessary balance between all of these component parts. Figure 1.2 illustrates the components which can be considered and which merge to define the overall weapon system capability.

**Figure 1.2: The Contribution of Agility to the Design Balance**



The operational capability of combat aircraft is achieved through the key attributes of performance, handling qualities, stealth and agility. Here, performance may be taken to include traditional airframe performance but also covers the on-board systems, sensors, armament capability and technology levels. Performance in isolation is not enough; detection can be prevented by stealth, turn rate can be countered by torsional agility etc.

Handling qualities implies user friendliness and the ability to exploit potential to the maximum. This equally applies to the pilot-vehicle interface (PVI) as it does to the airframe and engines.

Agility implies the ability to change state quickly, whether this be in manoeuvre, weapon selection, sensor mode or cockpit display information. It allows the aircraft to become unpredictable, and such a threat is hard to counter. In this sense, the term agility is what is referred to in this report as "Operational Agility".

For a Weapon System to be fully effective, it is essential that all of the contributing parts of the system should interact properly. As an example, consider the F-4 aircraft. This would not now be regarded as a particularly agile airplane, however, it was certainly one of the most effective. The reason for this effectiveness was that the airframe performance and handling capability matched the ability of the sensors, its radar, which matched its weapons characteristics. The design was well balanced.

There are examples of design imbalance which can be quoted, eg. the mismatch between short range air-to-air missile launch envelopes and a typical combat aircraft's flight envelope, between rapid target acquisition requirements and data path communication times, between turn performance and torsional agility, between stealth configuration restraints and performance and manoeuvre requirements, etc.

This points the way forward for future aircraft. Achievement of this design balance requires all of the Weapon System's attributes to be studied, evaluated and weighed against each other to determine the optimum solutions. This may require significant compromises if the required roles and perceived threats are sufficiently diverse. The possible effects of a design imbalance or the choice of the inappropriate technical compromise places emphasis on the techniques used to evaluate the design options. Clearly, adoption of some form of unifying evaluation methodology would be beneficial.

### 1.2.2 Evaluation Concepts

At present, no such total evaluation capability exists which has been fully tested and validated, although partial evaluations of some of the aspects involved have been undertaken.

The concepts involved with Operational Agility can assist in the design and evaluation of such Weapon Systems and should certainly be used in the formative, pre-specifications phases of work. To facilitate this, it is necessary to define the terminology used in discussion of Operational Agility. From the Working Group discussions, it became very clear that such definitions would be extremely useful if the complex arguments which have surrounded agility discusssions in the past were to be understood and put into context.

To achieve the design balance not only needs the definitions of agility, it also requires standardised agility figures of merit, together with a proven quantification methodology applicable from concept through design, test and into operational contexts. The role for the vehicle will give rise to differing weighting factors for the agility attributes, influencing the design balance.

The achievement of a cost effective design balance and the maximisation of Weapon System combat effectiveness are central to the concepts of Operational Agility.

### 1.3 Definitions of Operational Agility Terminology

1.3.1 ***Operational Agility*** is defined as ***the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.***

Operational Agility conveys the "big picture", in that it relates to the overall combat effectiveness of the airborne Weapon System. It relates the combat effectiveness to the weapon system design and to maximisation of the performance of the system. It is one of the elements that has an associated cost and cost may provide an upper limit on the level of Operational Agility that is achieved. The context includes all elements which are contained in the airborne vehicle and specifically excludes all other ground or airborne systems with which it might have to interact, although the interfaces with these external systems are included.

It is measured by the time to perform a mission task at an agreed level of precision for the task output. The measures are workload dependent. Agility can decrease as workload increases as the crew spend more time attending to the systems.

To measure Operational Agility, it is necessary to specify the nature of the task which should itself be defined as a response to the environment to cause a desired mission outcome and change in that environment. An example would be:- (i) to protect ones own ship as opposed to (ii) launch flares or decoys in response to an incoming attack. The first task has a number of options attached to it and requires the design to shape the specific actions to cause an outcome, whereas the second leads to the design of a cockpit to control a sub-system. The first approach allows a focus on the net effect of each aspect and allows comparisons of the effectiveness of the differing systems and solutions.

It should be born in mind in assessing Operational Agility, that time may be a variable within the control of the crew and that for the results to be meaningful, the precision has to be specified. The task is completed only when the desired mission outcome is achieved. As an example, a design option may have a higher turn capability, but accept a poorer shot accuracy. In such a case a success criterion may relate to the number of shots on target and were these sufficient to achieve a kill?

1.3.2 ***Transient Agility*** is a continuously defined property reflecting the instantaneous state of the system under consideration.

It is measured as an instantaneous physical property of the response of the vehicle or system. These properties include all the measureable time variant parameters which can be used to describe the behaviour.

1.3.3 ***Airframe Agility*** is defined by the physical properties of the aircraft which relate to its ability to change, rapidly and precisely, its flight path or pointing axis and to its ease of completing that change. As such, airframe agility is comprised of manoeuvrability, the ability to change magnitude and direction of the velocity vector, and controllability, the ability to change the manoeuvre state through rotation about the centre of gravity, independent of the flight path vector, or by a change of control power or engine response. As such, airframe agility relates closely to, and may be regarded as an extension to, flying qualities.

1.3.4 ***Systems Agility*** is defined by the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.

Systems agility covers sensors, displays and cockpit controls, targeting systems, missile management systems and their ability to interact both with each other and with the pilot. As with airframe agility, a time based metric is appropriate for these aspects, if defined with a precision target.

**1.3.5** ***Weapons Agility*** is defined by the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures.

It addresses the weapons sensor and its interface to the aircraft sensors, the launch delays and release aspects, the weapons performance in terms of manoeuvrability and weapon airframe agility, range and duration and its lethality and ability to avoid counter-measures. As such the weapon mirrors the airframe that launched it in many respects.

**1.3.6 Metrics for Evaluation Concepts**

***Experimental Agility Metrics.*** Experimental agility is defined from the completion of a discrete manoeuvre, such that it can be readily established during system evaluation and design, or from flight test. Often such metrics are compound properties, as exemplified by torsional agility which relates the ability to roll and manoeuvre in pitch simultaneously.

***Operational Agility Metrics.*** Operational agility is defined by the completion of a mission task element within the defined precision for the task and with a prescribed aggressiveness. The metrics relate to measurement of the time taken to complete the task to the satisfaction of the pre-set criteria.

## 1.4 Analysis of the Missions

When Operational Agility is a either a design objective or a customer requirement, the starting point for the subsequent work must be an analysis of the roles that the aircraft is required to fulfil. Traditionally, this has been an Operational Analysis task but, logically, it appears that this task should be extended to integrate much more closely with the initial design perturbations. The key is to let the perceived threat dictate the technologies that must be included or afforded in determining the design parameters of the vehicle.

### 1.4.1 Operational Agility Aspects for determining the Design Balance

Operational Agility concepts can and should be applied at the outset of the design process, starting even with the Operational Analysis work. The objective is to determine the correct design balance between airframe aspects, weapons and the onboard systems with a view to maximising the operational effectiveness at an affordable cost and to ensure that there is adequate growth potential in the aircraft to take it through its Service life.

Typically, combat aircraft have to remain in Service for around 20 to 25 years. During this time, the onboard systems can be upgraded many times, as the changing needs of the operational environments dictate. However, the airframe is much harder to make any fundamental changes to, implying that the flexibility has to be built in at the outset. Provided this is recognised early in the design process, before detail work starts, then it is more easily accommodated. Adding capability later is always more expensive, and may need major structural repair work.

It could be argued that provision of margins on the design to allow for future upgrades will enhance the Operational Agility of the aircraft by influencing life-cycle aspects, eg. the F-15 and Hawk aircraft were originally designed with wing hardpoints for external store carriage, although the specifications for these aircraft did not call for this capability. In the case of the F-15, the adage of the time was "not a pound for air to ground" but the capability was built in by McDonnell.

In the report chapters which follow, the key elements of Operational Agility will be discussed in detail, illustrating how the concepts may be applied to achieve the desired design balance and maximise the effectiveness of the combat vehicle in its various roles.

### 1.4.2 Mission Task Element Aspects

One of the Key concepts which the reader will become familiar with is that of "Mission Task Elements". The basic idea is to break down any mission into small enough segments that it is possible to analyse the processes which are going on in the vehicle or any of its systems at the time in question. As an example, a designer might be evaluating a cockpit design and layout in an attempt to optimise the displays and pilot actions that are necessary to perform a

number of possible functions that a scenario could demand. In this case, it essential to understand the flow of information to the pilot and what actions he would need to take. The cockpit displays would be defined to assist understanding and not provide unnecessary information which could serve to confuse or mislead.

The process of breaking down the tasks into the elemental parts is defining "Mission Task Elements". Use of this concept can be made in any area of the design, whether it be airframe, avionics or sensors, etc. It provides a means of identifying what is needed for the mission and is an essential tool in establishing that the design is properly balanced. The concept is most powerful when combined with a rapid prototyping facility, where candidate designs can be laid out, studied and altered quickly in order to achieve the required performance and flexibility.

Combining the concepts of Mission Task Elements with the metrics which will be discussed in some detail later in the report allows for a powerful analysis capability by which the various design trades can be determined and an optimum for purpose way forward found.

The helicopter community already use mission task element concepts in defining the handling qualities necessary for the vehicles, see ADS 33C for example. However, the concepts would appear to be applicable to a much wider range of topics than just handling qualities. Use of mission task elements as an analysis tool, for both design and evaluation, including flight test, is central to maximising the Operational Agility of any combat vehicle.

### 1.4.3 Specification Implications

Following Operational Agility approach should lead to a revised method for specifying future air combat systems. Often in the past, the specifications have provided contractual performance targets without the opportunity to question if the targets were really optimised to generate the most effective combat vehicle. For the future, use of the Operational Agility approach provides a methodology for establishing the relative worth of the differing performance requirements. Further, the methodology will enable the quantification of the trade-offs between the different systems.

However, for this to come about, the process of deriving specifications in use today will have to evolve to include Operational Agility criteria as definite requirement that the design should meet.

As a consequence, it is possible that future specifications will define the roles that the vehicle must fulfil and allow negotiation as to how best to meet these roles. Operational Agility concepts and metrics will allow the justification of the decisions with clarity. Once these decisions are made, then it will be possible to employ the same techniques to perform the detail design tasks and prepare the detail equipment specifications for manufacture. Finally, the techniques will allow the evaluation of the resulting systems from an operational effectiveness viewpoint.

It should be recognised that not all of the appropriate metrics have yet been defined or evaluated and that much work still remains before a complete set of metrics can be put forward. This report indicates the form these metrics should take and the framework within which they would be expected to work.

## 1.5 The Framework for Operational Agility

This report examines the subjects associated with Operational Agility with a view to providing the reader with sufficient background to follow the concepts which have evolved and allow an understanding of how all of the differing aspects relate to one another. To achieve this, the report has been structured into a number of Chapters, each of which can be treated either as a stand alone document or as a section of the total report.

The report addresses the Flight Mechanical aspects associated with Operational Agility in some depth, mainly because this is the area where most work has been performed in the past and this is frequently the starting point for many readers. However, the report strongly recommends consideration of the total design balance, including the systems and the weapons, the pilot and the design of his "office" if a truly cost-effective and agile Weapon System is to result from the specification, design and evaluation process.

During its work, the Group has found ways of characterising Agility and quantifying it by meaningful metrics, originating in the Flight Mechanics areas, but which are generally applicable across all the disciplines involved in

the design of a modern, highly integrated combat aircraft. The report attempts to provide illustrations of the metrics which result in these "non-traditional" agility areas.

The report concludes its discussion of Agility with a Chapter devoted to Evaluation. In its original concept, this related to evaluation by flight test but, again, it was realised that evaluation starts before the design even leaves the drawing boards, or the computerised design world in which it first gestates. Flight test is often assumed to be the last in a long line of formal evaluation processes. In reality, evaluation will continue throughout the vehicles life as pilots continually find different tasks that they can perform or different ways of performing old tasks!

Finally, the conclusions which the Group feel are most significant have been drawn out and presented, together with an assessment of those areas where we feel most benefit will be accrued from future work. As an example, it could be concluded that improvements in the Avionics, Displays, and the way in which the human pilot interacts with the data they present to assimilate the data as information, and Weapons are the areas which would provide greatest return on investment, at the moment, as airframes are already pressing upon the physiological limits of the human body.

*This should not be taken as a statement that will be true for all time as advances in technology have a habit of rendering such simplifications untrue in a very short measure of time. Such a statement should be reviewed for each new project.*

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Agility as a Contribution to Design Balance
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# Chapter 2 Airframe Agility

## 2.0 Introduction

Within the context of Operational Agility, airframe agility is by far the most mature element. Airframe agility has received the greatest attention and therefore has the largest source of available literature. Knowledge was gathered from both the fixed and rotary wing communities. This exercise was very rewarding as fresh exchanges of concepts strengthened the broader process of developing airframe agility.

The chapter will begin by first detailing the flight mechanical aspects of the airframe agility. The important motion parameters will be identified then used to develop equations using the differential geometry approach. To discuss the level of agility for design purposes the motion must be described quantitatively. This discussion provides an improved understanding of moderate and large amplitude manoeuvring. A method for relating control design requirements to the motion characterisations is also suggested.

From this foundation, the vast array of agility metrics will be briefly described and classified within an organisational structure. This structure will facilitate a clear deliniation of agility as a design objective and clarify the key characteristics for specifying agility. The discussion of each metric will include sample data presentation formats, relations to design criteria where known, and assignment of attributes that summarise the available knowledge. A sample application of the metrics to a missile engagement scenario will be used to emphasise the metric organisation framework.

It has been recognised that classical performance and flying qualities do not fully characterise the transicnt characteristics of the aircraft. Agility therefore developed as an extension of those concepts and is highly influenced by these concepts. Special emphasis will be placed on combining the requirements of agility and flying qualities to arrive at asuitable design that is capable of meeting its mission requirements. Aggressiveness as it influences the level of agility will also be studied.

Airframe agility design principles will then be presented from the perspective of mission requirements and the airframe agility concepts. The airframe agility design process will be addressed with four key aspects. Configuration layout which dictates manoeuvrability and performance. Structural design which provides upper limits on manoeuvrability. Stability and control, controllability and flight control system design which relates handling qualities design criteria, stability criteria, response and quickness. Powerplant integration which relates to performance, control and which for rotary wing vehicles may dictate the limit on manoeuvrability.

Finally, the evaluation of airframe agility as well as lessons learned from limited experience will be presented. An evaluation philosophy will be suggested that is based on the experience of numerous research organisations. The approaches and results of simulation and simulator studies will then be presented. The results of experimental flight tests will also be described although these are far too limited at this point in time. Agility data analysis techniques will be mentioned as well as current suggested specification methods.

Throughout this chapter, critical gaps will be identified that will assist with focussing future limited research efforts. These gaps will be highlighted where applicable. Conclusions and recommendations will also be made in each section.

Ib

## 2.1. FLIGHT MECHANICS

### 2.1.1. Introduction

The present section describes in some detail the analytical background needed to represent the motion of a flight vehicle from the standpoint of operational agility.

Although the traditionally dominating aspects of the motion are three-dimensional, both point mass and attitude equation need to be considered, the latter furnishing the necessary bridge required for the definition of control power and control histories necessary to achieve a given agility level.

The basic concepts of differential geometry are introduced as they are the basis for a description of the motion of an object in space. In addition, the most common reference frames and their notation will be presented. A brief description of traditional figures of merit used in practice, such as energy maneuverability, bleed rate, turn rate, etc., is given, followed by a summary of "agility" equations as they are available in literature.

A comparative evaluation of the different approaches is then performed with the idea of presenting how they can be seen as different aspects of the same physical problem.

An important part in the characterization of agile maneuvers is their feasibility in terms of control power and flight control system requirements. In this area not many guidelines are available, firstly because experimental activities are currently underway and still incomplete, secondly because results are still somewhat sensitive to availability in the present context.

Nevertheless, some comments will be made regarding the use of dynamic inversion as a technique with potential application in terms of dictating the control from angle of attack, sideslip and body rates necessary to achieve specific agile maneuvers. Finally, a brief description of some simulation results illustrating agile maneuvers will be presented.

### 2.1.2. Traditional Figures of Merit

Traditionally, dynamic effectiveness has been viewed in terms of familiar properties such as performance and maneuverability. Several parameters emerged in the past, which have led to some of the presently used agility metrics (see section 2.2. for more details on metrics).

The most important property of a combat aircraft is its ability to maneuver [1]. This can be expressed by climbing, acceleration and turning characteristics. The main parameter used to express climbing characteristics is termed specific excess power $P_S$. Usually, lines of constant excess power can be drawn in a standard altitude-Mach number diagram since $P_S$ is defined as the rate of change of the specific energy $h_e$.

A fighter aircraft which enters at a higher energy level (expressed by altitude and Mach number) and is able to maintain this superiority on the strength of greater excess power, has the advantage. If, on the other hand, it enters the combat at a lower energy level than its opponent, it will use the higher excess power in moving to a higher energy level within a very short time, so as to outmaneuver is opponent. This way of considering energies is known as energy maneuverability and is an essential part of a pilot's training.

An example of energy maneuverability curves used for performance and combat superiority evaluation is shown in figure 2.1.1. Contour diagrams with lines of constant specific excess power reveal where an aircraft has excellent maneuvering properties (see figure 2.1.1a for a load factor of 3 g). Lines with positive $P_S$ indicate the region of latent thrust potential usable for changing flight path, altitude, Mach number, etc.; of course the higher the excess power is the greater the combat advantage.

The same method can be used to compare the lines of $P_S = 0$ with each other for various load factors (see figure 2.1.1b). It can be seen that with an increasing load factor, maneuverability is considerably restricted. The aircraft which can tolerate a higher 'g', at a particular point in the curves has a significant advantage.

Figures 2.1.1c and 2.1.1d show two other different views of the same technique, the first in terms of wing loading and the second in terms of thrust to weight ratio. Lighter aircraft have the advantage in the lower Mach number range, thus allowing for tighter turns. The higher thrust to weight ratio at a given load factor extends the flight envelope and maneuverability of the aircraft.

One of the most important properties in terms of comparing airframe combat effectiveness has been the ability to turn. Turning flight performance can be represented as turn rate w versus Mach number for one particular altitude leading to the well known doghouse plots shown in figure 2.1.2.

Turn rate is the angle through which the turn radius sweeps in a unit time and it is given by the familiar relationship

$$\omega = \frac{g}{v}\sqrt{n^2 - 1} \qquad (1)$$

In order to achieve maximum maneuvering performance, the load factor must therefore be made as large as possible by means of the aerodynamic design of the aircraft. Equation (1) can be used to calculate, for one particular altitude, a whole set of curves, in which the load factor n appears as the parameter. The turn radius can also be easily calculated and a grid of realistic combinations of turn radii and load factors derived from which various aircraft design can be compared as shown in figure 2.1.3.

The above techniques have been used to establish maneuverability evaluations and they maintain their validity in this respect. The next sections will describe how to go further and how to set up an analytical framework for the analysis of another fundamental property of modern combat aircraft, that is airframe agility.

### 2.1.3. Differential Geometry Approach

Airframe agility has been studied in recent years as one of the components leading to the superiority of combat aircraft over the threat and defined as operational agility in this report. Although airframe agility has been measured through simulation and, more recently, in flight testing, it lacks a unified analytical background, thus explaining the plethora of metrics used for its definition and measurement.

A general agreement has been found among manufacturing, procuring and research agencies in that airframe agility is now associated with the rate of change of the maneuver plane and, as such, it has been recognized as a property of the flight path. The development of the governing equations is done using a differential geometry approach [2] and the main elements needed to describe the flight path in a three dimensional space are shown in figure 2.1.4.

We define as $\bar{R}(t)$ the position vector, $\bar{v}(t)$ the velocity vector and $|..|_E$ and $|..|_T$ the inertial and trajectory frames respectively. The geometric characteristics of the flight path can be developed independently of the aircraft speed by using the arc length $s$ rather than time as the explicit variable.

Consider an elementary trajectory arc length ds as shown in figure 2.1.5, define the unit tangent vector

$\bar{t} = \dfrac{d\bar{R}}{ds}$ , the following expressions hold:

$$\frac{ds}{dt} = |\bar{v}| \quad \bar{t} = \frac{d\bar{R}}{ds} = \dot{\bar{R}} \Big/ |\bar{v}| \qquad \bar{t} \bullet \bar{t} = 1 \quad and \quad \bar{t} \quad perpendicular \quad to \quad \frac{d\bar{t}}{ds} = \bar{t}' \tag{2}$$

The osculating plane is defined as the plane containing the unit tangent vector and its derivative with respect to arc length, thus instantaneously defining the plane in which the trajectory lies.

Define the unit normal vector $\bar{n}$ perpendicular to $\bar{t}$ in the osculating plane, then

$$\bar{n} \parallel \frac{d\bar{t}}{ds} \quad \text{therefore } \bar{n} = \frac{d\bar{t}/ds}{|d\bar{t}/ds|}$$

Finally, the third unit vector of the trajectory system (also called Frenet reference system) is the binormal vector

$$\bar{b} = \bar{t} \times \bar{n}$$

The above three vectors identify the flight path reference frame, which coincides with the instantaneous position of the point mass P along the trajectory.

Additional elements can be defined to characterize the geometrical properties of the flight path. From figure 2.1.5, the curvature of the trajectory is directly related to the variation of the angle ε with respect to an infinitesimal arc length change $ds$. Therefore we can set

$$\kappa = \left|\frac{d\varepsilon}{ds}\right| = curvature \qquad r = \frac{1}{\kappa} = radius \quad of \quad curvature \tag{3}$$

from which the relationship between normal and tangent unit vectors becomes

$$\bar{n} = \frac{1}{\kappa}\frac{d\bar{t}}{ds} \tag{4}$$

The curvature vector $\bar{\kappa} = \kappa\bar{n}$ represents the rate of change of the normal plane about the binormal unit vector.

The rate of change of the osculating plane about the tangent unit vector is called torsion and it is represented by the symbol $\tau$. Torsion is zero for planar trajectories and it can be related to normal and binormal unit vectors as follows

$$\frac{d\bar{b}}{ds} = \frac{d}{ds}\left[\bar{t} \times \bar{n}\right] = \bar{t} \times \frac{d\bar{n}}{ds} = -t\bar{n} \tag{5}$$

In summary,

$$\begin{aligned} \frac{d\bar{t}}{ds} &= k\bar{n} \\ \frac{d\bar{n}}{ds} &= -k\bar{t} + t\bar{b} \\ \frac{d\bar{b}}{ds} &= -t\bar{n} \end{aligned} \tag{6}$$

Geometrically, curvature and torsion identify a vector $\Omega$ called the Darboux vector about which the trajectory frame rotates at each instant, this vector is shown in figure 2.1.6. The magnitude of the rotation rate can be expressed with respect to arc length or time as given in equation (7) below.

$$\left|\bar{\Omega}\right| = \sqrt{\kappa^2 + \tau^2} = \left|\bar{v}\right|\sqrt{\kappa^2 + \tau^2} \tag{7}$$

Note that k and t are intrinsic properties of a curve and are coordinate transformation invariant. One of the problems associated with the flight path description based on curvature and torsion, is their computation for cases other than simple ones. An alternative is to express curvature and torsion as a function of the inertial position vector and its time derivatives [3]. Considering the curvature first, we have

$$\dot{\bar{R}} = \dot{s}\frac{d\bar{R}}{ds} \qquad \ddot{\bar{R}} = \ddot{s}\frac{d\bar{R}}{ds} + \dot{s}^2\frac{d^2\bar{R}}{ds^2} \qquad \dot{\bar{R}} \times \ddot{\bar{R}} = \dot{s}^3\frac{d\bar{R}}{ds} \times \frac{d^2\bar{R}}{ds^2}$$

from which we can find

$$\kappa = \frac{\left|\dot{\bar{R}} \times \ddot{\bar{R}}\right|}{\left|\dot{\bar{R}}\right|^3} \tag{8}$$

Similarly for the torsion, it can be shown that

$$\tau = \frac{\left(\dot{\bar{R}}\ddot{\bar{R}}\dddot{\bar{R}}\right)}{\kappa^2\left|\dot{\bar{R}}\right|^6} = \frac{\left(\dot{\bar{R}}\ddot{\bar{R}}\dddot{\bar{R}}\right)}{\left|\dot{\bar{R}} \times \ddot{\bar{R}}\right|^2} \tag{9}$$

Based on the above results, velocity and acceleration of the aircraft can be expressed as a function of arc length, curvature and torsion

$$\begin{cases} \bar{v} = \dot{\bar{R}} = \dot{s}\bar{t} \\ \bar{a} = \dot{\bar{v}} = \ddot{s}\bar{t} + \dot{s}^2\bar{n} \end{cases} \tag{10}$$

Of course, the acceleration lies in the osculating plane of the trajectory. The flight path orientation in an inertial frame requires the introduction of three trajectory Euler angles $\lambda$, $\gamma$, $\sigma$ defined as

$$\begin{cases} \lambda = \text{ rotation about } \bar{k}_E \text{ or heading angle} \\ \gamma = \text{ rotation about } \bar{n} \text{ or flight pathangle} \\ \sigma = \text{ rotation about } \bar{t} \text{ or trajectory rollangle} \end{cases}$$

The Euler angles and torsion and curvature are related by an angular rate type relationship given by

$$\begin{cases} \dot{\lambda} = \kappa v \cos\sigma / \cos\gamma \\ \dot{\gamma} = -\kappa v \sin\sigma \\ \dot{\sigma} = \tau v + \kappa v \cos\sigma \tan\gamma \end{cases} \tag{11}$$

As an example of flight path description using differential geometry, consider a high speed yo-yo maneuver as described in [3]. The maneuver is idealized as a single sinusoid wrapped around a vertical circular cylinder with a 180 degrees heading reversal. The maneuver and its model are shown in figure 2.1.7. In this case, the position vector has the following components in the inertial space, where $\varsigma$ is the azimuth angle

$$\bar{R} = r\cos\varsigma\bar{i}_E + r\sin\varsigma\bar{j}_E - \left[h_0 + h_A \sin\left(2\varsigma - \frac{\pi}{2}\right)\right]\bar{k}_E$$

With numerical values taken from [3], the behavior of torsion, curvature and Euler angles as function of azimuth can be obtained as in figure 2.1.8.

## 2.1.4. Kinematic Aspects of Agility

From the established definition of rate of change of the maneuver state, we can determine the agility vector in terms of kinematic components or dynamic components depending of which side of Newton's second law we are interested in. Agility can be defined then as

$$\bar{A} = \frac{d\bar{a}}{dt} \tag{12}$$

thus in terms of kinematic variables, or as

$$\bar{A} = \frac{1}{m}\frac{d\bar{F}}{dt} \tag{13}$$

if the dynamic aspects need to be considered. If we concentrate on equation (12), we can express agility in components along the Frenet frame using either the derivation found in [4], [5], or a similar one based on time derivatives as in [6]. From [4], we have

$$\bar{A} = \dot{\bar{a}} = \frac{d}{dt}\left[\ddot{s}\bar{t} + \dot{s}^2\bar{n}\right] = \dddot{s}\,\bar{t} + \ddot{s}\frac{d\bar{t}}{dt} + 2\dot{s}\ddot{s}\kappa\bar{n} - \dot{s}^2\dot{\kappa}\kappa\bar{t} + \dot{s}^2\frac{d\bar{n}}{dt}$$

from

$$\begin{cases} \dfrac{d\bar{t}}{dt} = \dot{s}\kappa\bar{n} \\ \dfrac{d\bar{n}}{dt} = -\dot{s}\kappa\bar{t} + \dot{s}\tau\bar{b} \end{cases}$$

we obtain

$$\bar{A} = \left[\dddot{s} - \dot{s}^3\kappa^2\right]\bar{t} + \left[3\dot{s}\ddot{s}\kappa + \dot{s}^2\dot{\kappa}\right]\bar{n} + \dot{s}^3\kappa\tau\bar{b} \tag{14}$$

where

$$\begin{cases} A_A = \dddot{s} - \dot{s}^3\kappa^2 \\ A_C = 3\dot{s}\ddot{s}\kappa + \dot{s}^2\dot{\kappa} \\ A_T = \dot{s}^3\kappa\tau \end{cases} \tag{15}$$

The term $A_A$ is defined as <u>axial agility</u>, $A_C$ is called <u>curvature agility</u> and $A_T$ is the <u>torsional agility</u>. From a qualitative analysis it can be seen that curvature and torsion affect agility in that beneficial effects of $\kappa$ are found both in torsional as well as curvature agility, whereas the absence of curvature increases axial agility. This has led to other definitions of axial agility where the curvature term is neglected and only the third derivative of arc length is retained thus decoupling axial agility from the other two components.

The agility vector given by (14) can be also be written to highlight standard performance-maneuverability terms such as those described in section 2.1.2.. Following the derivation from [4], we obtain

$$\bar{A} = \left[\ddot{v} - \omega n_z g\right]\bar{t} + \left[3\omega n_x g + \frac{\omega^2}{\kappa^2}\dot{\kappa}\right]\bar{n} + \omega v^2\tau\bar{b} \tag{16}$$

where $\omega = v\kappa$ is the instantaneous turn rate, $n_x$ and $n_z$ are the axial and normal load factors, and $3\omega n_x = 3\kappa P_s$ is called kinetic specific excess power.

As mentioned earlier, the agility vector can also be expressed kinematically in terms of time derivatives and Euler angles as referred to the inertial frame. This approach was taken by Herbst and the investigators at MBB [6] to derive a framework for the development of agility studies which have led to the X-31 program.

Figure 2.1.9 shows the angular variables involved in the studies conducted by MBB. With different symbology, they represent the same angles defined in (11), that is $\mu$ = velocity bank angle, $\zeta$ = osculating plane inclination, $\gamma$ = flight path angle, $\chi$ = heading angle. The triples ($\zeta$, $\gamma$, $\chi$) and ($\sigma$, $\gamma$, $\lambda$) are therefore equivalent. The turn rate of the trajectory is then $\omega = v\kappa = \sqrt{\dot{\gamma}^2 + \dot{\chi}^2 \cos\gamma}$. The Darboux vector, indicating the rate of rotation of the maneuver plane can the be expressed as

$$\overline{\Omega} = \left[\dot{\zeta} - \dot{\chi}\sin\gamma\right]\bar{t} + \omega\bar{b} = v\left(\tau\bar{t} + \kappa\bar{b}\right) \tag{17}$$

and the lift bank angle $\mu$ is related to the above rotations by

$$\tan\mu = \frac{v\dot{\chi}\cos\gamma}{v\dot{\gamma} + g\cos\gamma} \tag{18}$$

The expression of the agility vector is now found in the usual manner by taking the inertial derivative of the acceleration and yielding

$$\overline{A} = \left[\ddot{v} - v\omega^2\right]\bar{t} + \left[2\dot{v}\omega + v\dot{\omega}\right]\bar{n} + v\omega\left[\dot{\zeta} - \dot{\chi}\sin\gamma\right]\bar{b} \tag{19}$$

Note that at this point there are several approaches in [6] leading to the definition of axial, curvature and torsional agility. If we follow [4], which gives equation (15), we can immediately define the three agility components from (19) as

$$\begin{cases} A_A = \ddot{v} - v\omega^2 \\ A_C = 2\dot{v}\omega + v\dot{\omega} \\ A_T = v\omega\left[\dot{\zeta} - \dot{\chi}\sin\gamma\right] \end{cases} \tag{20}$$

The description in (20) however poses some problems in that purely kinematical terms appear that are not related to force onsets (such as $-v\omega^2$ in the axial agility expression) and steady state components in roll are present. Reference [6] has a more complete description of possible alternatives among which is the definition of axial and curvature agility from (20) and a new definition of torsion agility as the change of roll turn rate of the osculating plane (or angular acceleration of the lift vector about the flight path), thus using the wind axis system. As an example, an alternate expression to (20) is given by

$$\begin{cases} A_A = \ddot{v} \\ A_C = \dot{v}\omega + v\dot{\omega} \\ A_T = \dfrac{d}{dt}\left[\dot{\mu} - \dot{\chi}\sin\gamma\right] = \ddot{\mu} - \ddot{\chi}\sin\gamma - \dot{\chi}\dot{\gamma}\cos\gamma \end{cases} \tag{21}$$

## 2.1.5. Dynamic Aspects of Agility

The development in the previous section concentrated on relating agility and trajectory. Another important aspect is the relationship between agility and the forces necessary to achieve it, in particular the control forces.

The relationship is intrinsic in the definition of agility and it is given by equation (13), where it is obvious the importance of the transient behavior of the applied forces rather than their steady state values as used in classical flight mechanics.

Since the applied forces can be expressed in several different reference frames, in addition to the inertial and Frenet ones, we list them here together with the appropriate Euler angles.

| | | | | | |
|---|---|---|---|---|---|
| $[..]_E$ | = | *inertial* | $[..]_E \Longleftrightarrow [..]_T$ | $(\sigma, \gamma, \lambda)$ | |
| $[..]_T$ | = | *Frenet* | $[..]_E \Longleftrightarrow [..]_W$ | $(\mu, \gamma, \lambda)$ | |
| $[..]_W$ | = | *wind* | $[..]_W \Longleftrightarrow [..]_S$ | $(-, -, \beta)$ | (22) |
| $[..]_S$ | = | *stability* | $[..]_S \Longleftrightarrow [..]_B$ | $( \ , \alpha, -)$ | |
| $[..]_B$ | = | *body* | $[..]_T \Longleftrightarrow [..]_s$ | $(\mu, -, \beta)$ | |
| | | | $[..]_T \Longleftrightarrow [..]_b$ | $(\phi, \theta, \psi)$ | |

There are three roll angles that are used to differentiate the orientation of trajectory, wind and body frames with respect to the inertial reference. It can be shown [3] that their relationship is given by

$$\phi = \sin^{-1}\left[\frac{\sin\beta\sin\gamma + \cos\beta\cos\gamma\sin(\mu+\sigma)}{\cos\theta}\right] \tag{23}$$

for the special case of coordinated flight and small angles, $\beta = 0$ and $\phi = \mu + \sigma$ .

The applied force in equation (13) can be written as

$$\bar{F} = mg\bar{k}_E - D\bar{i}_W + Y\bar{j}_W - L\bar{k}_W + T\bar{i}_B \tag{24}$$

equation (24) does not include thrust vectoring. If that were not the case, vectoring angles can be included and the thrust will have components along the other body axes as well. Using the appropriate coordinate transformations from (22), we can express (24) in the Frenet frame as

$$\bar{F} = F_{XT}\bar{t} + F_{YT}\bar{n} + F_{ZT}\bar{b}$$

where

$$\begin{cases} F_{XT} = -mg\sin\gamma - D + T\cos\alpha\cos\beta \\ F_{YT} = mg\sin\sigma\cos\gamma + Y\cos\mu + L\sin\mu + T(\cos\mu\cos\alpha\sin\beta + \sin\mu\sin\alpha) \\ F_{ZT} = mg\cos\sigma\cos\gamma + Y\sin\mu - L\cos\mu + T(\sin\mu\cos\alpha\sin\beta - \cos\mu\sin\alpha) \end{cases} \tag{25}$$

Now, using (25) in (13), we can write the agility vector in terms of applied forces and their derivatives

$$\bar{A} = \frac{1}{m}\left[\left(\dot{F}_{XT} - \omega F_{YT}\right)\bar{t} + \left(\dot{F}_{YT} + \omega F_{XT} - F_{ZT}\frac{\dot{\zeta} - \dot{\chi}\sin\gamma}{v}\right)\bar{n} + \left(\dot{F}_{ZT} + F_{YT}\left\{\dot{\zeta} - \dot{\chi}\sin\gamma\right\}\right)\bar{b}\right] \tag{26}$$

Equation (26) has been written using turn rate and trajectory Euler angles for the purpose of comparing the components with either (20) or (21). In a similar manner, equation (26) can be compared with (15) using as variables velocity, curvature and torsion. Also, for consistency, the trajectory Euler angles notation used in [6] has been retained.

The kinematic and dynamic agility components are then related by equating (12) and (13), yielding

$$\begin{cases} A_A = \ddot{v} - v\omega^2 = \dot{F}_{XT} - \omega F_{YT} \\ A_C = 2\dot{v}\omega + v\dot{\omega} = \dot{F}_{YT} + \omega F_{XT} - F_{ZT}\dfrac{\dot{\zeta} - \dot{\chi}\sin\gamma}{v} \\ A_T = v\omega\left[\dot{\zeta} - \dot{\chi}\sin\gamma\right] = \dot{F}_{ZT} + F_{YT}\left\{\dot{\zeta} - \dot{\chi}\sin\gamma\right\} \end{cases} \tag{27}$$

or

$$\begin{cases} A_A = \dddot{s} - \dot{s}^3\kappa^2 = \dot{F}_{XT} - \nu\kappa F_{YT} \\ A_C = 3\ddot{s}\dot{s}\kappa + \dot{s}^2\dot{\kappa} = \dot{F}_{YT} + \nu\kappa F_{XT} - F_{ZT}\tau \\ A_T = \dot{s}^3\kappa\tau = \dot{F}_{ZT} + F_{YT}\nu\tau \end{cases} \tag{28}$$

It is evident from equations (27) or (28), that agility is influenced by the changes in force magnitude due to controls (in this case angle of attack, sideslip, bank angle and thrust) as well as force rotation due to the instantaneous change of the maneuver plane and control changes due to the turn rate term.

An important aspect that needs to be addressed at this point is the need of computing the aircraft control variables associated to a specific trajectory characterized by a given level of agility which can be obtained from equation (15) or (20) depending on the approach. This problem is, in general, very complicated for arbitrary trajectories in that it involves the solution of a two-step dynamic inversion procedure.

Once airframe agility characteristics are specified in terms of curvature, torsion, velocity and the three trajectory Euler angles (say λ, γ, σ), the control strategy must be obtained from the solution of (11), (28) plus equations for lift and drag, yielding angle of attack, sideslip, bank angle and thrust. This of course not always has a solution and parameter identification algorithms are necessary. Presently such work has not been done and more research activity is suggested.

A second consideration is the computation of surface deflection histories generated by agile maneuvers and body rates. Since, according to our definition, agility is governed by changes of the maneuver state, the moment equations can not be used directly, but they need to be incorporated through the maneuver plane angular rate. Again, a dynamic inversion process is involved. Once the control variables are obtained, body rates can be found, at least in principle, through which control deflection can also be computed from the moment equation equilibrium.

Briefly, if we define the aircraft angular rate in body axes as

$$\overline{\Omega}_{BE} = \overline{\Omega}_{BT} + \overline{\Omega}_{TE} \tag{29}$$

an expression for body rates p, q, r can be found of the form

$$p, q, r = f[\alpha, \beta, \mu, \kappa, \tau, \nu] \tag{30}$$

equation (30) can then be used to compute roll, pitch and yaw accelerations $\dot{p}, \dot{q}, \dot{r}$ . The solution for control surface deflections is computed via inverse problem from the relation $[I]\dot{\overline{\Omega}}_{BE} = M_{\delta}\delta$ . Again, a complete solution is not yet available, but the above description could provide a general framework for it.

In summary, a flight mechanical framework can be set up to examine airframe agility in terms of trajectory components, force components and control histories, although this latter aspect has not been fully developed yet. The use of dynamic inversion is suggested as well as the use of attitude projection [7]. The procedure described above is schematically shown in figure 2.10.

### 2.1.6. Maneuvers for Agility Evaluation

One of the more critical problems in the analysis of aircraft agility is the definition of sample maneuvers to be carried out by the flight vehicle. In this respect several factors need to be considered among which is the difficulty of treating the tactical component during aerial combat. In addition, the diversified origin of airframe agility metrics has led to the absence of a standardized set of trajectories to be used for agility analysis as well as synthesis.

Within the framework of this chapter, we can however identify some characteristics needed by a trajectory in order to highlight properties such as axial, curvature and torsion agility.

Since axial agility is dominated by the rate of change of longitudinal acceleration, the main controllers involved are the engine and any other longitudinal input such as aerobrakes and spoilers. This leads to a maneuver which is essentially unidimensional and tractable independently of the other two. A standard axial agility maneuver is therefore characterized by straight level flight with associated acceleration/deceleration due to actuator changes.

A possible curvature agility maneuver can be thought as given by a maximum performance level turn starting at straight level flight with given speed and altitude, or starting at a given level turn condition (maximum sustained turn rate) as shown in figure 2.1.11.

A possible torsion maneuver could involve a maximum performance turn reversal at constant turn rate as shown in figure 2.1.12. In both cases, the measured parameters are curvature and torsion agility as given by (15) o (20).

Another trajectory involving post stall maneuvering has been proposed in recent years leading to the definition of a joint US-German research program with the design of the X-31 aircraft. This maneuver, also known as the Herbst maneuver [6], is presently undergoing experimental evaluation through extensive flight testing and is a typical example of curvature and torsion agility combination over four segments of the flight path:

- pitch up/climb: mainly curvature, very little torsion
- roll upside down: some curvature to the reverse side but high peak of torsion
- slice: marginal curvature but significant initial torsion
- dive out: constant level of curvature with very little torsion.

The general structure of the trajectory is designed such that the maneuver takes place primarily in the vertical plane. The main control functions are angle of attack and wind roll angle with the thrust set at maximum afterburner.

The initial phase consists of a climb to decrease speed while increasing the flight path angle. The angle of attack reaches its maximum lift value then remaining essentially constant. The second segment initiates with a sharp roll when the flight path reaches a preset value up to a 90 degree roll angle. Then the roll angle is kept constant until the heading reaches a critical value (with rates of change of the order o 80 deg/sec). The actual poststall is accomplished in the third segment as the aircraft rolls to a 180 degree value. This slicing maneuver is also characterized by changes in angle of attack beyond the stall value due to the loss of speed experienced in the previous two phases. Since this segment is prior to recovery, the flight path angle must be reduced to level flight so that the aircraft can dive, thus entering the fourth segment of the trajectory. The recovery phase consists essentially of a dive to recover speed from the gained altitude and it accounts for about half of the total maneuver time. Here both control are active, but the angle of attack makes the largest contribution of course. A schematic representation of the maneuver is shown in figure 2.1.13.

At the present time, the X-31 program is undergoing flight testing to evaluate the Herbst maneuver and to investigate the use of such capabilities for future air combat. Unfortunately no flight test data is available at this writing, nor pilot comments. An idea of how agility components change during the Herbst maneuver can be obtained from three-dimensional computer simulation results found in [6]. Some of the results are shown in the next three figures which trace curvature, torsion and axial agility over the entire trajectory. Each figure contains more than one plot, each one corresponds to a particular definition of agility component as derived from equation (19). The interested reader can find additional details in ref. [6].

Pitch, roll and yaw agility measurements can also be obtained through simulation and evaluated during standard maneuvers typical of air combat. Figure 2.1.17 shows a simulated yo-yo maneuver between two aircraft during a one-to-one gunnery air combat. Aircraft A has additional thrust vectoring capabilities that produce an edge over aircraft B [8].

### 2.1.7. Conclusions

This section has illustrated some of the tools that can be used as an analytical framework for the analysis of airframe agility and for the derivation of agility metrics. A general consensus has been found in relating agility to the trajectory changes and therefore to a characterization in terms of flight path related variables such as rate of change of curvature, torsion, turn rate and trajectory roll angle. Differential geometry appears a natural setting for this type of study.

An activity still open for research and experimentation is the computation of control required to achieve specified agility characteristics. This could ultimately lead to flight control system specifications for agility. The problem, however, requires dynamic inversion at the trajectory as well as attitude levels and solutions can not be found without using parameter identification schemes. The lack of experimental data compounds the problem.

### 2.1.8. References

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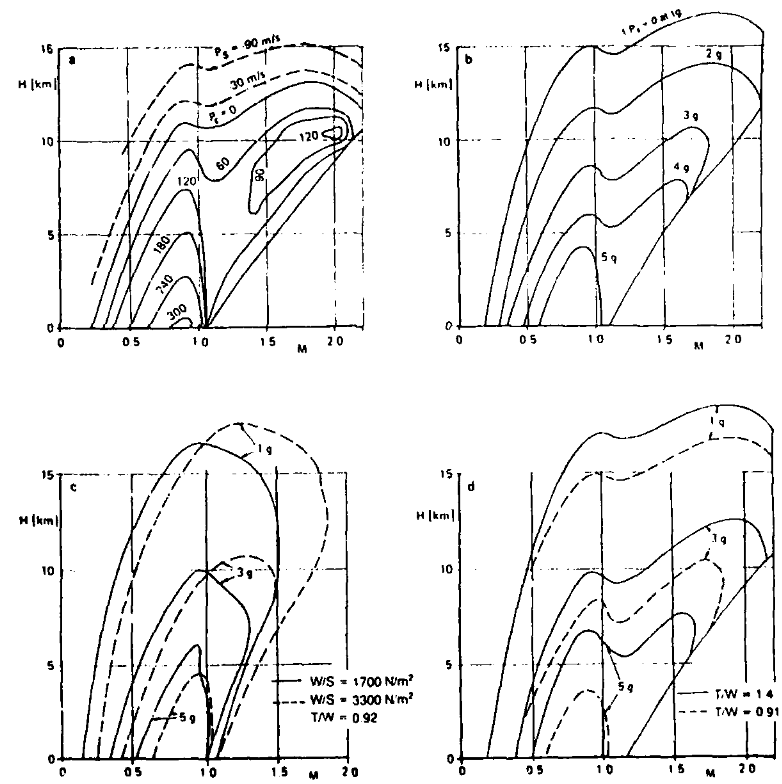



Figure 2.1.1. Energy-Maneuverability Curves [1]

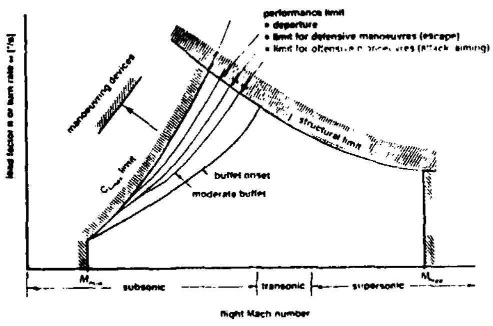



Figure 2.1.2. Maneuvering Limits for Combat Aircraft [1]

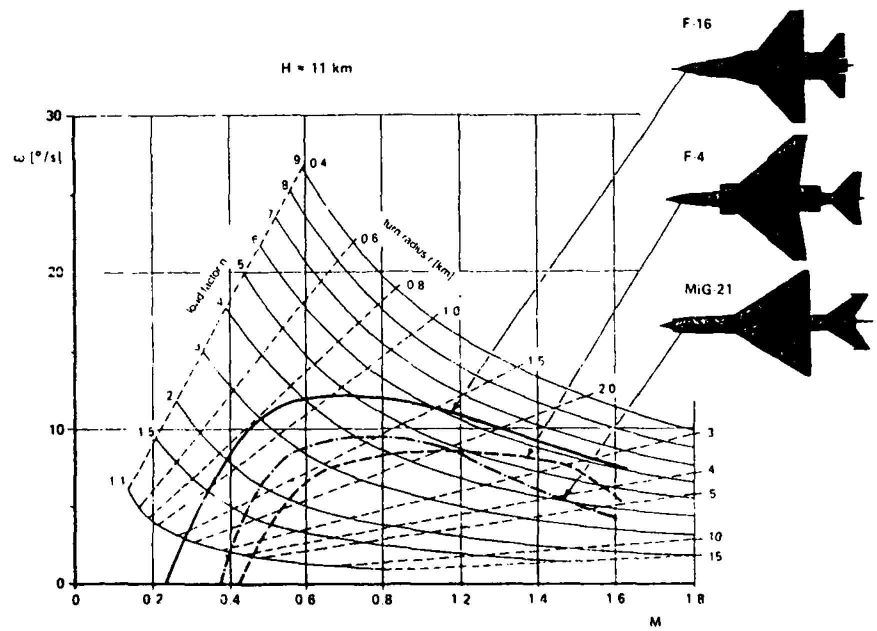



Figure 2.1.3. Maneuvering Performance of different Aircraft

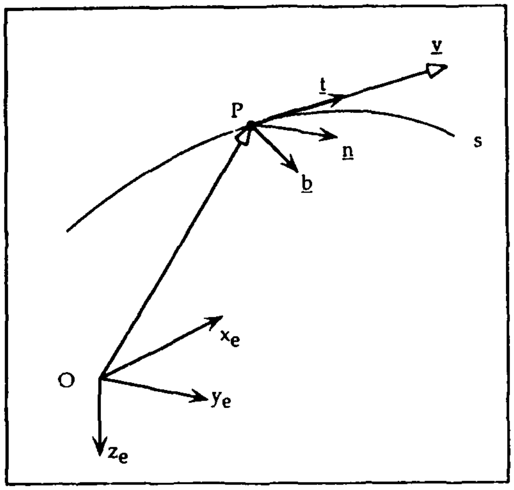



Figure 2.1.4. Reference Frames for Trajactory Analysis

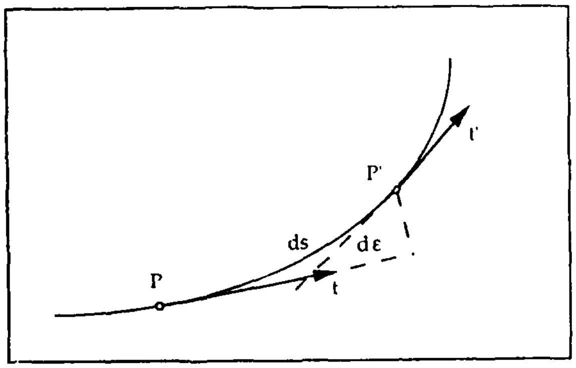
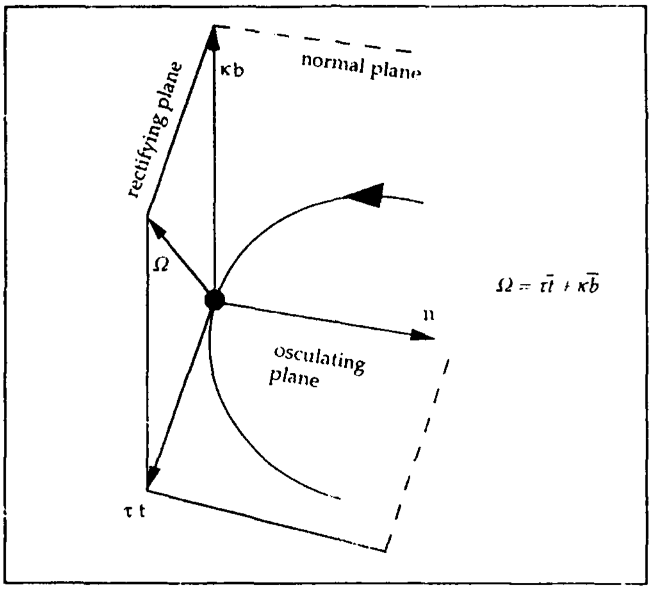



Figure 2.1.5. Elementary Arc Length Parameters




$\Omega = \tau \bar{t} + \kappa \bar{b}$

Figure 2.1.6. Geometry of the Darboux Vector

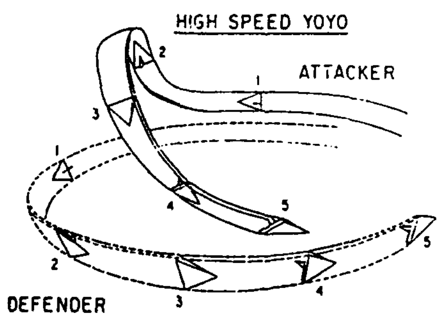



Figure 2.1.7. Yo-Yo Maneuver [3]

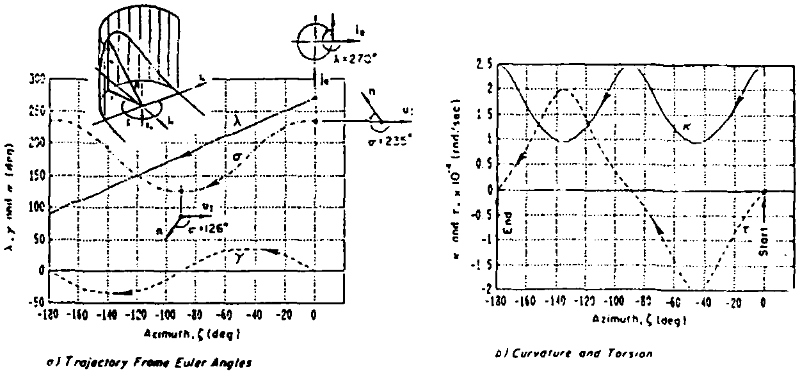



Figure 2.1.8. Trajectory Parameters for Yo-Yo Maneuver [3]

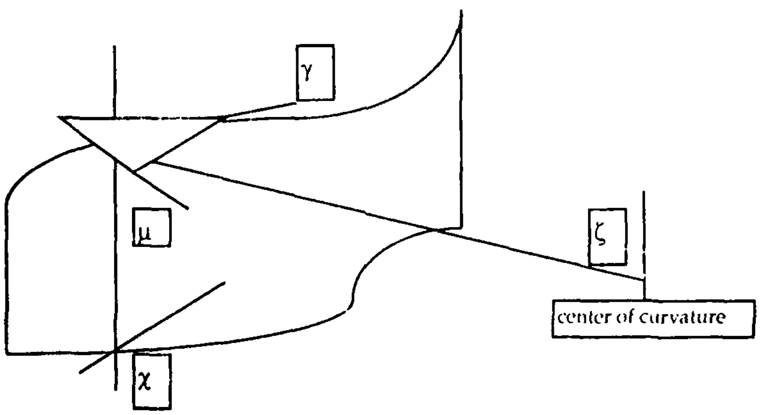



Figure 2.1.9. Angular Elements used in [6]

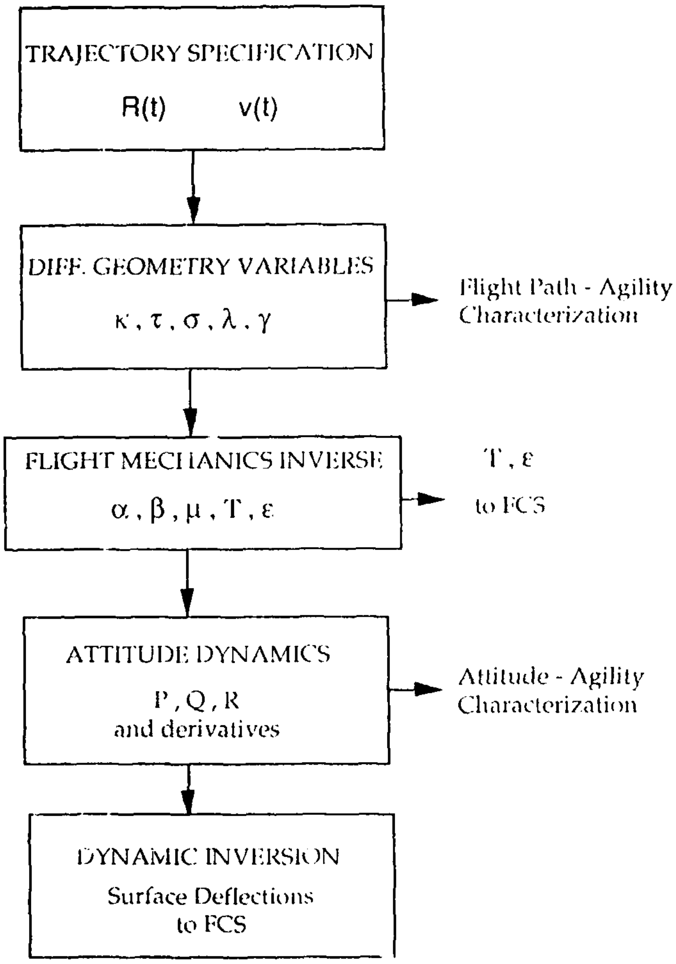



**Figure 2.1.10. Procedural Block Diagram for Agility Analysis**

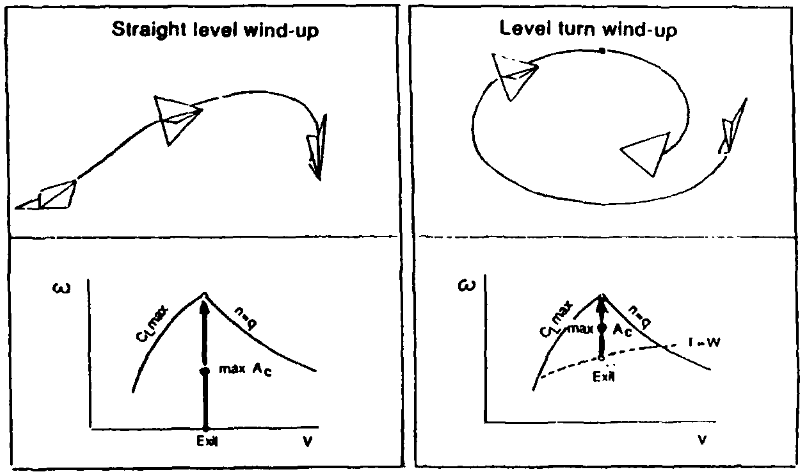



Figure 2.1.11. Typical Maneuver for Curvature Agility Analysis [6]

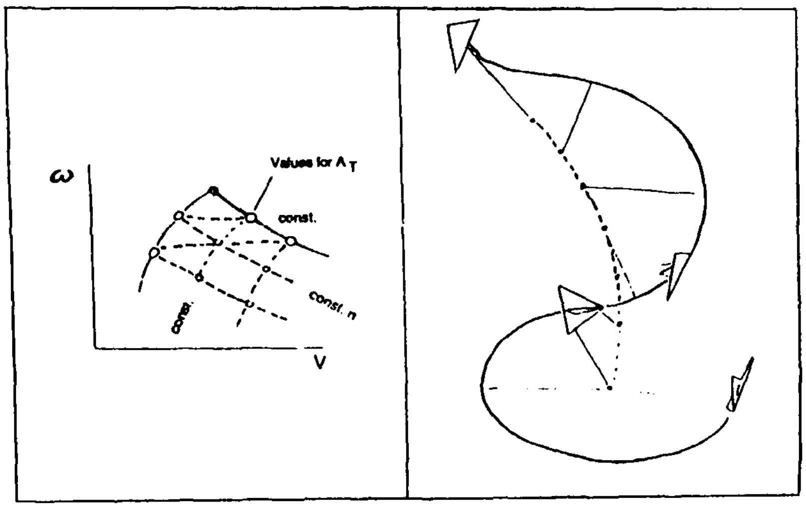



Figure 2.1.12. Typical Maneuver for Torsion Agility Analysis [6]

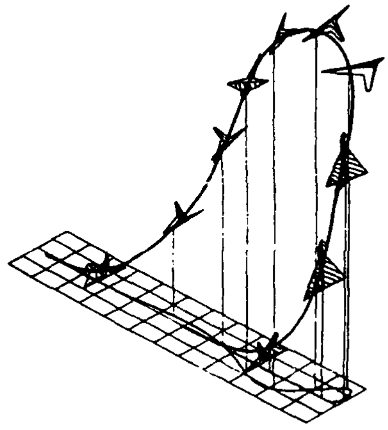


Figure 2.1.13. Post-Stall Maneuver [6]

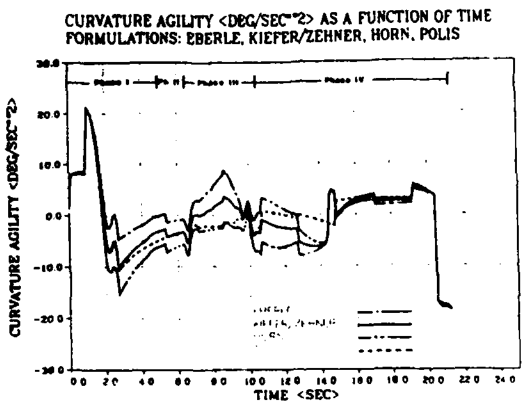



Figure 2.1.14. Simulation Results for Curvature Agility [-..- from (20), -.- from (21)]

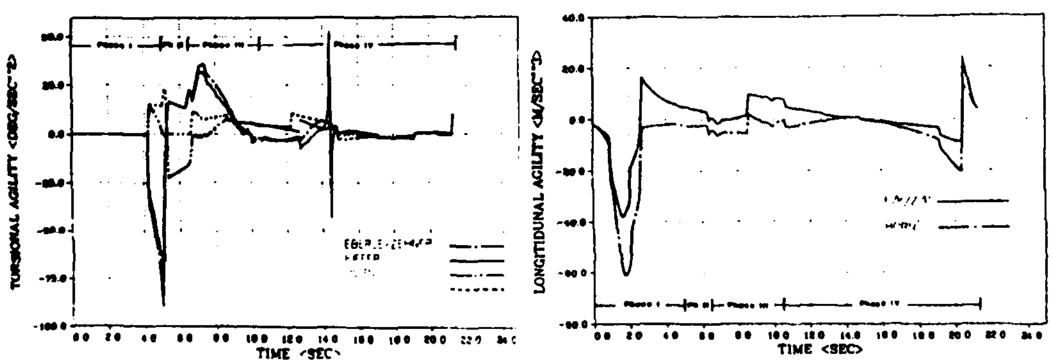
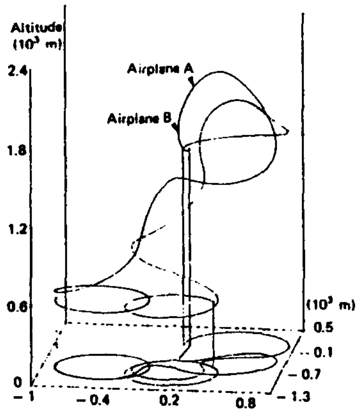



Figure 2.1.15. Results for Torsion and Axial Agility [-..- from (20), -.- from (21)]



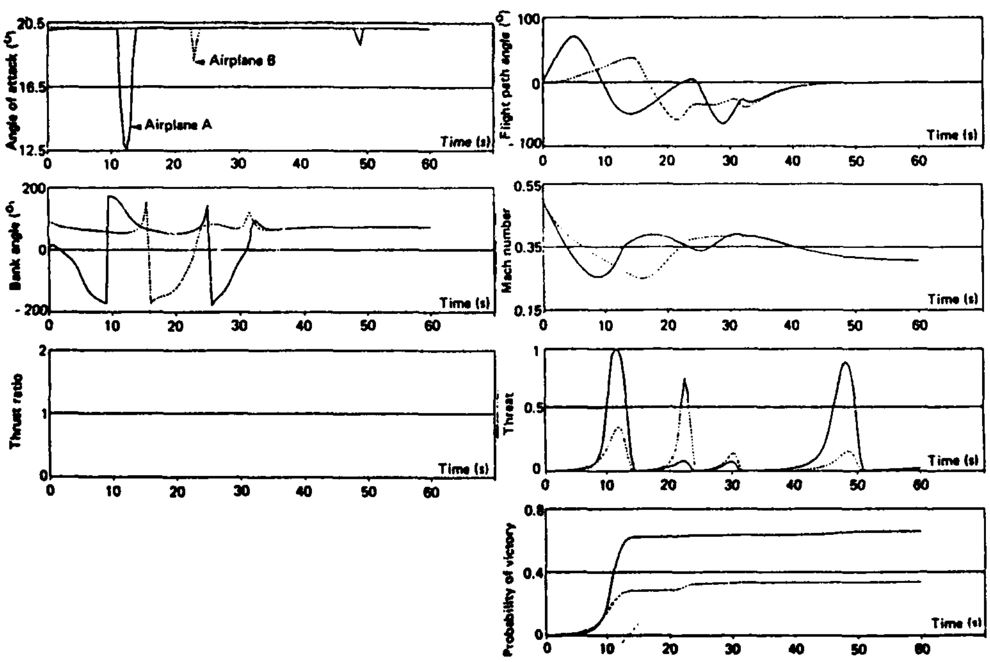




Figure 2.1.16. Results for Yo-Yo Maneuver from [8]

## 2.2 Airframe Agility Metrics

### 2.2.1 Introduction

This chapter continues the development of agility with a discussion of the various tools currently available to characterize airframe agility. Chapter 2.1 developed the theoretical basis for airframe transient agility. This chapter will expand on those ideas by identifying aircraft motion parameters which quantify agility, describing the current agility metrics.

The subject of characterizing agility has been the focus of a great deal of research. Two main perspectives have been established. First, the evaluation community has long sought for more understanding of the differences between various aircraft which have defied existing means. The second, being the design community which has sought to include new technologies such as thrust vectoring, higher thrust engines, and improved aerodynamic control at high angles of attack. When researchers attempted to combine the two perspectives confusion was created because the term agility was always associated with the subject. Simultaneously, the operational community has wondered what all the innovation will do if anything to future tactics. The challenge in this discussion is to attempt to bring all the existing research and lessons learned into one logical structure for understanding airframe agility and how it fits together with the evolving concept of Operational Agility.

As with previous flight mechanics characterizations, metrics or measures of airframe flight behavior have first been developed to structure the key components of the concept. Airframe agility metrics are required to provide figures of merit on the transient maneuvering capability of a combat aircraft. These figures of merit provide: a basis for specifying the level of agility required, data for aircraft designers, and a framework for the evaluation of the agile aircraft. These requirements must be achieved while ensuring that the final product is suitable for its intended mission. As agility should not be considered and treated as a stand-alone aircraft characteristic it is convenient to link it to existing and well defined principles of describing aircraft flying characteristics. To facilitate the development, the definitions presented in section 1.1.1 should be considered:

> Operational agility is defined as the ability to adapt and respond, rapidly and precisely, with safety and poise to maximize mission effectiveness.
>
> Airframe agility is defined as the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path or pointing axis and to its ease of completing that change.

From these definitions, come the constituent elements of the agile maneuver implied by the concepts of **rapid** and **precise** change in maneuver states. The wealth of agility literature essentially supports these two characteristics as the central components for each metric. Another key point is that for transient maneuvering, maneuver state has been interpreted to be a nose pointing direction or flight path attitude state. Furthermore, the ease of completing the airframe state change overlaps with flying qualities concepts. This aspect supports the argument that airframe agility is simply an extension of flying qualities. Finally, to obtain operationally meaningful agility data the control inputs must be applied with mission representative maneuvers. This may not feasible or practical in some cases such that some metrics may require that "special" flight test or experimental maneuvers be developed.

The most difficult aspect of characterizing transient agility has been the selection of aircraft motion parameters which quantify agility. Ongoing research, has indicated that existing parameters as well as some new ones provide a clear measure of agility. Unfortunately, what is still lacking is sufficient flight test data to identify the most operationally meaningful time dependent parameters.

This section will first develop a classification scheme for organizing the airframe agility metrics proposed in the literature. These metrics will then be grouped within these classes along with a brief desciption and simplified presentation formats. Attributes to characterize the state-of-the-art in terms of ease of measurement, data availability, relation to design and relation to operational effectiveness as is currently understood will be be assigned to each metric. The section will be concluded with an example of how the metrics and classes would be applied to a transient combat engagement.

### 2.2.2 Agility Metric Classification Development

Metric classification development has not been conducted with the same level of effort as has the study of each specific metric. Fortunately, some classification schemes have been proposed. These schemes will be presented and then expanded to match the scope of Operational Agility. To be useful and acceptable to all communities a classification scheme must be developed which accounts for the wide range of possible missions and aircraft types. Formulating a classification scheme is seen to be an important step in the establishment of agility as a design objective because the operationally significant elements of agility need to be clarified and specifications developed.

#### 2.2.2.1 Original AFFTC Agility Metric Classification

The first widely accepted agility metric classification scheme was adopted by the AFFTC and attempted to classify metrics by initial response and long term response of fighter aircraft. This classification scheme separates the metrics into what was referred to as either transient and functional metrics. These categories were originally defined as: (27)

> Transient metrics. Referring to those parameters that characterized the acceleration or deceleration portion of a maneuver.
>
> Functional metrics. Are those characteristics that described the complete system including the pilot-vehicle interface, control mechanisms, aircraft performance, aircraft handling characteristics as the total system behaved in closed loop tasks.

The transient metrics provided agility information for designers to isolate the response and evaluators to compare data for specification compliance. Functional metrics, provided information about the operational suitability of the airframe.

#### 2.2.2.2 Revised Metric Classification (AFFTC)

Recently, researchers at the AFFTC have elected to change these metric classification titles to more accurately represent the use of the agility metrics. This alteration was reported by Lawless (1) after compilation and analysis of data obtained between 1987 and 1989 on five aircraft types was completed.

> Agility Design Parameters (ADP) replaced transient metrics as a means to provide a clearly defined design tool. These metrics characterized the onset and capture transients in the pitch, roll, and longitudinal axis.
>
> Agility evaluation metrics were proposed to replace functional metrics as a means of classifying the closed loop tasks. This class was intended to include entire maneuvers as the ultimate goal of the designer for which an aircraft can be fully evaluated. Within evaluation metrics, a further two categories: flight path and attitude metrics were suggested. Fight path agility included the pilot control of the lift vector comprised of load factor agility, torsional agility, and acceleration along the flight path. Attitude agility covers nose pointing including pitch and yaw pointing.

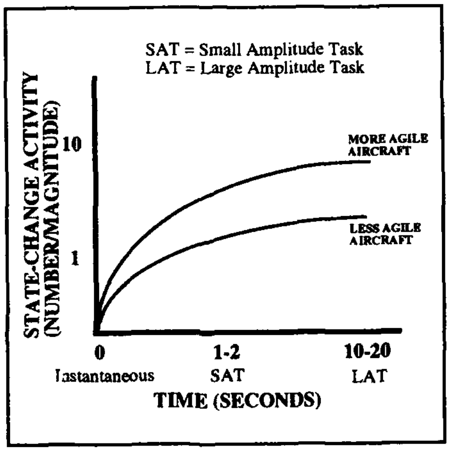
The revised scheme reflected the purpose of the metrics from the perspective of the user. Lawless suggested that, if flown correctly, test maneuvers could generate data for both transient and functional metrics. In fact, the report also suggested that if onset, steady-state, and capture data were gathered correctly as ADPs, that a suitable model could be developed from which to obtain the desired functional metric data. This issue will certainly require further investigation.

Clearly, multiple time regimes of interest are being proposed by these structures. Intuitively, short-term and long-term are the primary regimes.

2.2.2.3 Time-Scales for Agility

Further proposals were presented by Dorn in the area of time-scales for agility.(7) Dorn discussed a systematic approach to classifying agility metrics through focusing on state-change versus time plot presented in Figure 2.2.1. This plot illustrates the state change conceptually comparing two different aircraft. More state changes per unit time implies more agility. As the time increment approached zero the number of state changes also may be expected to approach zero implying that there exists a realistic short time interval at which point the concept of agility is no longer meaningful, ie. a pilot cannot make control inputs in .01 sec intervals starting from time=0. Long time interval inputs (albeit complex sequences of inputs) tend to be performance dominated. There exists a region between the very short and very long interval which requires investigation. This structure therefore seems to imply three time regimes for agility: short-, medium-, and long-term.

Figure 2.2.1 State-Change Activity versus Time Plot. (7)




Dorn suggested that three techniques could be used to investigate the time regimes of this plot. These techniques were differentiation, change of variable, and time-energy integration. This approach provides a means of generalizing metrics possibly identifying were gaps exist in the current array of metrics. In essence, these techniques provide a global view of agility. Each technique is roughly comparable to each of the previous classes. The techniques are:

<u>Differentiation</u>. Owing to the time dependance of agility, Dorn suggested that in addition to velocity and acceleration, the third order term jerk may become significant.

<u>Change of Variables</u>. This technique substitutes a time-weighted parameter into an independent variable. Dorn uses the turn rate divided by the time to roll through 90 degrees as an example.

<u>Time-Energy Integration</u>. This technique plots the specific energy over a predefined time interval while a mission related maneuver is performed. The area between the zero loss specific energy line and the task dependant line provides a measure of the vulnerability of an aircraft and Dorn referred to it as the aircraft's "energy-agility". Dorn also suggested that this technique may be useful in weighing the task time for a time increment associated with each task element of the maneuver.

Since the agility concept is inherently time dependant, time scales have been proposed as a basis for metric classification. Dorn proposed a "three time scale" classification scheme to isolate the significant time realms of agility. Using the state-change versus time plot shown in Figure 2.2.1, the time scales proposed were:

instantaneous (inst) rates possessing 0-1 second duration.

small amplitude task (sat) lasting 1-2 seconds or time to do small amplitude tasks.

large amplitude task (lat) lasting 10-20 seconds or a mission segment of an entire mission task.

Dorn also suggested that each of the time-scales was a building block for the next longer scale. It is important to observe that along with the quickness, the state-change activity is also important. Figure 2.2.1 illustrates that to be a superior agile aircraft that both short time and high activity must be achieved. In terms of complexity then, the agile task could be a change of a single aircraft state or many states. Therefore the concept of task sequence must also be considered. This implies that task elements could be performed in series or to achieve a shorter time, in parallel. Dorn suggested that the rolling in a loaded condition is a good example of this parallel state change condition. This makes classification of metrics by axes of motion very complex.

This classification scheme was supported by Fox (3), who classified the metrics as:

Analytical metrics including all mathematical manipulations of the governing equations of motion.

Experimental metrics including all metric obtained from trajectory simulation or actual flight tests.

Fox (3), interpreted Dorn's time-scales by identifying the dominant agility metrics in use by the community. Instantaneous agility is the mathematical differentiation of the governing equations of motion as developed in Chapter 2.1. Small amplitude Task agility is dominated by Skow's metrics and large amplitude task agility dominated by Kalviste, Tamrats, Dorn's energy-agility metric. Each of which will be discussed later. Also in favor of this approach were researchers from Aermacchi (12).

Interestingly, the approach proposed by the AFFTC is also consistent with a time dependant approach since transient behavior is short term and functional long term.

Overall, Dorn's approach is important because of the inclusion of the input amplitude and task complexity. The time scales relate to the metric structure developed thus far. The instantaneous rates time region can be considered the same as the transient metric class. Small amplitude tasks relate to the experimental metric class. Large amplitude tasks relate more to an operational metric class. The working group discussed at length the quantitative time increments for each metric class and determined that these should not be articulated precisely. The real benefit of defining three classes of metrics come from their purpose and suitability for breaking down a complex motion into useable components for the design, evaluation, and operational communities.

2.2.2.4 Operationally Oriented Mission Tasks

One final issue must be discussed before a complete metric structure is presented. The operational suitability aspect of the transient characteristics has not been completely addressed. The classification schemes proposed by Lawless, Dorn, and Fox primarily reflected the interest of the design and evaluation communities. By changing the closed loop task oriented metric class from "functional" to "evaluation/experimental", the scope and purpose of the classification has been limited to use by the evaluation community. Like flying qualities metrics, it is conceivable that a functional metric classification also includes operational metrics that can be sensibly linked to effectiveness. This would enable data to be gathered for specific engineering purposes as well as operational purposes. This idea of an operational metric class can find its basis in ADS-33C, the rotary wing flying qualities specification.

An accepted method for including operational characteristics has been with the use of mission task elements (MTE). The MTE was first officially proposed in ADS-33C as a means for standardizing helicopter flying qualities

evaluations during operational tasks. It can be defined as any operational task with an unambiguous start and end point. The MTE has been useful for flying qualities (handling qualities during tracking) evaluations and could be used also for agility evaluations. Example MTEs include split-S, yo-yo, etc as used in Chapter 2.1 examples. In practice, a mission profile or series of mission profiles can be defined. The profiles can then be broken down into many MTEs. Since a MTE may not be suitable for evaluation, the MTE can be further broken down into MTE segments which break the maneuver down into its lowest level of complexity as very short time slices.

2.2.2.5 Airframe Agility Metric Structure

The metric structures just presented provide a firm foundation on which to build a sensible classification scheme. Three broad classes of metrics can now be defined: transient, experimental, and operational. These classes are defined in Table 2.2.1.

Table 2.2.1 Agility Metric Classification Structure.

| METRIC CLASS | DEFINED BY | MEASURE |
|---|---|---|
| TRANSIENT | Continuously defined property of response | A physical property of the response |
| EXPERIMENTAL | Completion of a small task | Compound property eg:torsional agility |
| OPERATIONAL | Completion of a mission task element | Time for completion, precision, aggressiveness |

The transient class may be considered to contain continuous characterizations of the transient response. In other words, the continuous metrics include all the instantaneous parameters developed in chapter 2.1. These metrics can be calculated at any moment for any maneuver. They lend themselves to optimization, most likely maximization, as suggested by Murphy etal (6).

From this continuous characterization of the motions, certain characteristics can be formulated into "discrete" parameters to focus on the transient response to a control input. These are the experimental metrics. They are only calculated at specific moments immediately after a specific input is applied. These metrics are more appropriately associated with the initial response in particular axes of motion (single or compound). As previously discussed experimental metrics are the basic building blocks for maneuvers. They may be broken down into pure translational (forward, sidewards, or vertical translations of the center of gravity in a linear sense), nose pointing (orientation of the body axis with respect to the velocity vector or direction of lift/maneuver plane), and torsional (rotation of the lift/maneuver plane about the velocity vector).

Operational metrics are the final class and focus on the global agility concepts of quickness and precision and specific mission metrics. The mission task quickness metrics focus on the time to perform a task associated with a mission. Aggressiveness plays a significant role in weighing the time to perform the task. The mission task precision focus on the accuracy with which the task is controlled while being performed quickly.

When put together, these concepts provide a structure with which to organize any agility metric. These titles will be maintained throughout the remainder of the discussion with the addition of sub-categories to further refine the organization. The hierarchical nature is reflected by the level of interest catering to either the design, evaluation, or operational communities.

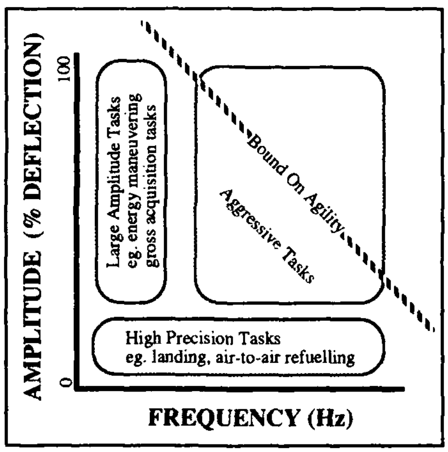
2.2.2.6 Maneuver Aggressiveness

Before proceeding further, it is worth considering the aspect of the control input amplitude and its influence on the results derived from the agility metrics. The WG17 report discussed the lack of formal recognition of moderate and

large amplitude handling criteria. Intuitively, these types of maneuvers are the basis for agility and provide a clear link with existing handling qualities concepts.

Figure 2.2.2 illustrates the amplitude and frequency/time characteristics for any maneuver isolated into a single axis. Close inspection of this plot reveals where flying qualities research has emphasized small amplitude precision tasks. On this plot, the other areas that have not received wide recognition are more obvious. The central region is not well understood. This area represents moderate to large amplitude and moderate to high frequency inputs and is intuitively the realm of agility. Bise and Black argued that "by proper enumeration of the tasks (inputs) and desired responses (outputs), any maneuver including agile maneuvers may be described completely. Agile responses are then seen to be simply a subset of all possible responses"(15). This characteristic implies a dependence of maneuvering on the aggressiveness of the input. An issue that makes flight test repeatability of real concern. One area which is related to aggressiveness is defining the maximum performance limit or bound. This definition will depend on flying qualities during aggressive maneuvering, structural, aerodynamic, and physiological limits. These issues will all need to be combined and understood better in order to determine a realistic aggressiveness quantification scheme. Increasing amplitude and faster responses therefore implies more aggressiveness. A term that the working group has had a great deal of trouble defining. To arrive at a viable classification scheme then, the relation of maneuver aggressiveness to the metrics must be established. This issue will be discussed further in 2.2.5 as well as 2.3.

Figure 2.2.2 Control Input Amplitude versus Frequency Plot.




2.2.2.7 Metric Attributes

A large number of agility metrics have been proposed that usually lean towards the primary area of study of each community. Since it is one the this working group's aims to bring the available knowledge together in a meaningful way, a method was devised to label each metric apart from the overall classification scheme in order to gauge usefulness and acceptability. The attributes selected to best perform this function were:

A Easy to measure/test/fly with clearly defined success criteria for the task or task element

B Supported by a substantiated available database (1-simulation, 2-experimental flight test,3-operational flight test)

C Related to mission effectiveness

D Related to design or design parameters

For combat aircraft the best measure of metric usefulness is the mission effectiveness. Once demonstrated useful, it becomes a matter of gathering the data and application to the design. Unfortunately at this early stage of agility development, the metric may be identified as useful, easy to gather, and applicable to the design, yet there is insufficient data available to designers or tacticians to provide guidance. The data availability rating is critical to directing future research efforts.

Fortunately, three complementary methods are available for building the data bases. Of these, simulation has become widely available and therefore a primary source of relatively cheap data (especially multiple aircraft engagements). The current research effort was summarized by Dorn in (7) for the fighter aircraft and was geared for air-to-air combat. The majority of metrics have evolved from this effort. No similar summary for rotary wing research has yet been accomplished which would be geared to nap-of-the-earth stealth and concealment. This should be the focus of future rotary wing research.

2.2.2.8 Symbology

Prior to discussing the metrics and how each fits into the broader framework of Operational Agility, symbology, subscripts and greek letters used in the literature are defined.

**Symbology**

| | |
|---|---|
| A* | Agility Metric Class |
| ax | axial acceleration |
| AQP | attitude quickness parameter |
| $A_f$ | agility factor |
| CCT | combat cycle time |
| DST | dynamic speed turn |
| G,g | acceleration due to gravity |
| H | altitude |
| he | specific energy |
| HQR | handling qualities rating |
| LA | lateral agility |
| M/A | maneuverability/agility |
| Nz | body axis normal load factor |
| Nz,w | wind axis normal load factor |
| P,p | roll rate |
| PM | pointing margin |
| Ps | specific excess power |
| PR | power rate |
| PN | roll rate normal load factor product |
| Q,q | body axis pitch rate |
| R,r | yaw rate |
| RES | relative energy state |
| RSD | rearward separation distance |
| TA | torsional agility |
| TR | turn rate |
| T | time interval |
| t | time |
| $t_k$ | time to kill |
| $t_{k/r}$ | time to kill and recover to original energy state |
| U | forward airspeed component |

**Subscripts**

| | |
|---|---|
| b | body axis |
| f | final time |
| i | initial time |
| inst | instantaneous |
| lat | large amplitude tasks |
| o | zero time |
| pk | peak value |
| RC90 | roll and capture 90 degrees |
| sat | small amplitude tasks |
| w | wind axis |

**Greek Letters**

| | |
|---|---|
| $\alpha$ | angle of attack |
| $\beta$ | angle of sideslip |
| $\delta$ | time increment |
| $\Delta$ | change increment |
| $\psi$ | heading angle |
| $\phi$ | angle of bank |
| $\gamma$ | flight path angle |
| $\theta$ | pitch angle |
| $\tau$ | time delay |
| $\omega$ | turn rate |

## 2.2.3 Transient Agility Metrics

Transient agility metrics are those time dependant parameters that characterize airframe state changes. These metrics are continuously defined properties reflecting the instantaneous state of the airframe. Clearly, many suitable metrics already exist, but some gaps are present that require more metrics be defined. These gaps are: large amplitude maneuvers; transition events; and acceptable maximum performance criteria. The theoretical development of maneuverability and agility discussed in chapter 2.1 detailed the characteristic equations of motions which are the transient agility metrics. As emphasized in 2.1, the primary focus is on the rate of change of the maneuver plane. The metrics are summarized in Table 2.2.1 including traditional metrics. Assignment of attributes has been difficult because very little data are available. The majority of the results has been obtained from simulator studies but some results were obtained in reference 1. Practical results for implementing this approach should be studied further.

Table 2.2.3.1 Transient Metrics.

| Metric Title | Metric Parameter | Source | Attributes |
|---|---|---|---|
| Energy Maneuverability | Ps, $\omega$, Nz | Boyd | A,B, C, D |
| Maneuverability of the flight path | $d\underline{V}/dt$ | Jouty | B1,B2,B3,C,D |
| Attitude Maneuverability | $\phi$-dot, $\theta$-dot, $\psi$-dot or P,Q,R | Jouty | B1,B2,B3,C,D |
| Agility Vector | $d\underline{a}/dt$ | Mazza | A,B1 |
| A-Vector Components | $A_A$, $A_L$, and $A_T$ | Mazza, Herbst | B1,D |

Attribute Codes:

A Easy to measure/test/fly with clearly defined success criteria for the task or task element

B Supported by a substantiated available database (1-simulation, 2-experimental flight test,3-operational flight test)

C Related to mission effectiveness

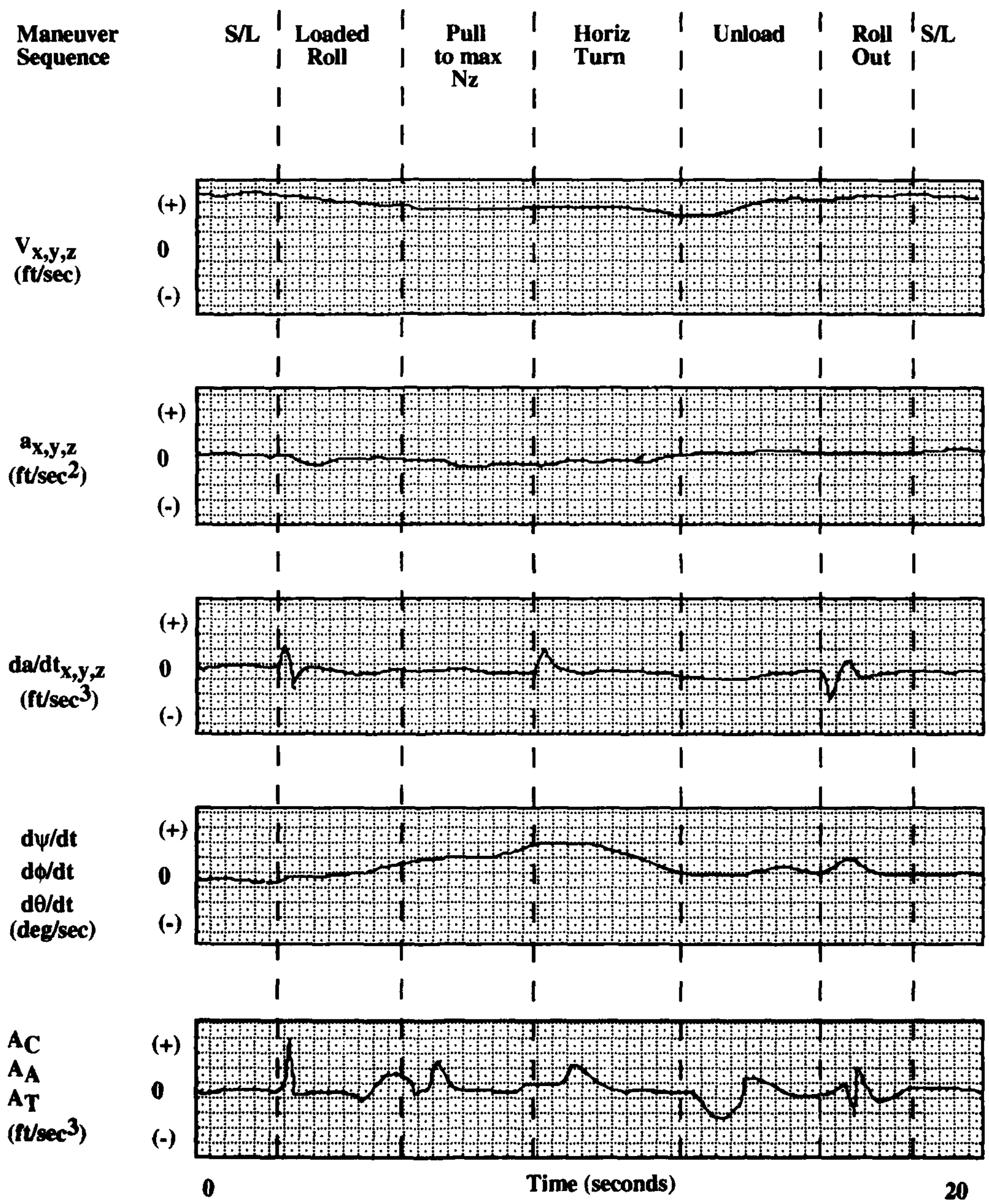
D Related to design or design parameters

### 2.2.3.1 Data Presentation

The presentation of the metric information is best achieved through a time history plot. Examples of which are shown in Figures 2.14 and 2.15. The presentation will reflect local maxima that indicate when the state transition is occurring and what are its characteristics. Figure 2.15 illustrates peak events in the agility vector components. This clearly demonstrates that in a "real" maneuver sequence, *the agility characteristics occur only at key moments, depending on the maneuver.* Figure 2.2.3 shows how the various metrics might be presented together for a hypothetical maneuver sequence. The data for this figure is arbitrary.

The continuous nature of these metrics are such that they may be defined at any point in time during flight and have an infinite possible set of solutions. Therefore, for the metrics to be useable, the control inputs and flight conditions must be detailed. This aspect is discussed in 2.1.6 and the maneuver aggressiveness notion discussed in 2.2.2.6. Variation of the design parameters will also change these characteristic equations and therefore the results, a process that lends itself to maximization. Whether the absolute maximum is desirable is determined by coupling the analysis with the experimental and operational metrics. The continuous time history of the motions also provide a vehicle with which to prove compliance with specifications. An issue that will be discussed in 2.5.

Figure 2.2.3 Time History Plot of Transient Agility Metrics for a Maneuver Sequence.(Fictional Data)



Energy Maneuverability. The classical E-M parameters were discussed in section 2.1.2. The doghouse plot is the normal method for presenting the complete capability of the aircraft. At any moment in time, the aircraft state is described by a single point on this plot. This presents a limitation for analyzing transient motions. E-M data can be presented as a time history but the parameters must be converted to another form. Examples are: breaking Ps into rate of climb and $a_x$ ; Nz as a component of the Maneuverability of the Flight Path group; and turn rate as an Attitude Maneuverability group. None of these conversions are new but when combined with all three axes of motion, transient maneuvers in multiple degrees of freedom can be more accurately described and analyzed.

Maneuverability of the Flight Path. The accelerations describing the flight path are those at the center of gravity. Isolating these parameters emphasizes the performance capabilities of the aircraft and the force equations of motion.

Attitude Maneuverability. The angular motions emphasize the nose pointing maneuvers. The body rates are important for controllability studies. The euler rates are important when considering the attitude maneuverability of the aircraft with respect to an adversary aircraft.

Agility Vector. This vector and its components are described in section 2.1.

## 2.2.4 Experimental Agility Metrics

Experimental metrics have been proposed to aid the evaluator in breaking down any maneuver into segments which are repeatable and controllable yet provide information applicable to the overall mission. In other words, experimental metrics obtain engineering data from a maneuver segment and would be handled in a flight test program as per traditional flying qualities metrics. As far as the relation between transient and experimental metrics is concerned, the transient metrics characterize the flight mechanics regardless of the maneuver whereas the experimental metrics characterize particular building blocks of the motion commanded by the pilot.

### 2.2.4.1 Axis of Motion Classification

Most of the proposed agility metrics fall into the Experimental metrics class and have had numerous sub-classifications suggested. The axis classification which has been widely used are the categories of flight path control and nose pointing. Structures have been proposed in references 1,3, 6, 7, and 14.

NASA Axis Breakdown. An axis breakdown for organizing agility control design metrics was suggested by NASA (6) which included: axial, pitch (vertical-plane maneuvers), turning (horizontal-plane maneuvers), nose pointing, and roll (torsion). These were determined by the conventional degrees of freedom controlled by the pilot. The pitch agility was broken into vertical, horizontal turning, and nose pointing displacements relative to the velocity vector for isolation of an aircraft's response. Murphy etal noted that vertical pitch response isolated longitudinal system dynamics whereas horizontal pitch response included lateral-directional system dynamics. This approach was suitable for detailed discrete analysis of transient response. Since a conventional fixed wing aircraft was considered, the only translational axis considered was the axial direction. A more general breakdown would have to include vertical and sidewards translations as would be expected for helicopters or VSTOL aircraft. In addition to the breakdown by axis, Murphy etal also proposed that the design metrics also be in the form of either passive or active metrics. From (6), a passive metric was defined as one which is computed after the design is specified or tested and an active metric was defined as one that is continuous functions of the system dynamics or continuous time functions of states and controls and can be used for optimization. This differentiation was significant because it identifies those characteristics which may exist at any moment during a transient maneuver and those which would exist at a discrete moment. Up to this point many metrics have been used interchangeably.

Rockwell Hybrid Structure. Bitten prepared a comparison of available metrics (14) and grouped them according to the breakdowns used by MBB, Eidetics, AFFTC and General Dynamics. This scheme was applied to all the available metrics in 1989. The MBB approach included: longitudinal axis (direction of the velocity vector), curvature agility (direction of the maneuver plane), and torsional agility (rotation of maneuver plane about the velocity vector). The remainder used: pitch agility, lateral agility, axial agility as the primary breakdowns. From these structures, Bitten suggested that agility be broken down into: longitudinal/axial (in direction of velocity vector), pitch/curvature (direction of lift/maneuver plane), and roll/torsional (rotation of the lift/maneuver plane about the velocity vector). This breakdown was based on fixed wing type aircraft so again, the translational metrics do not include sidewards and vertical motion of the center of gravity. This structure also does not adequately address the requirements of the body axis nose pointing with respect to the flight path of the center of gravity.

This working group suggests that the experimental metrics be classified as translational, nose pointing, and torsional.

### 2.2.4.2 Translational Metrics

The translation metrics include those metrics which focus on the transient changes in translation state variables or pure linear motion of the center of gravity. This class of metrics are dominated by performance characteristics of the aircraft. These include the changes of: position (start to stop); the magnitude of the individual components of the velocity vector; and accelerations. These metrics are only concerned with the pure changes in either the forward, sideward, or vertical motion states. Aggressive changes in translation state would be characterized by quick times and maximum peak values. These characteristics would not include rotational changes of state ie. zero angular rates.

For complete data sets, the axial performance of the aircraft is usually expressed at 1g as well as other meaningful increments. As such, some overlap with longitudinal flight path bending will occur. Current translational agility metrics are shown in Table 2.2.4.

Airspeed Capture Time. This metric measures the time to accelerate forward from a start airspeed and capture a final forward airspeed. This metric is expressed as:

$t_{UC} = t_{Uf-Ui}$ where $U_f$ is the final airspeed, and
and $U_i$ is the initial airspeed.

This metric has not been widely used and therefore no definitive database is available. Measurement would not be complicated as long as the airspeed conditions are defined. Potential definitions for the fixed wing case would be an initial airspeed after the engagement phase and final airspeed at or above the corner velocity. For the rotary wing case, hover to dash and vice versa would be meaningful. This metric could be defined by a mission task element (see 2.2.5). Data presentation would depend on configuration, gross weight, altitude, and power setting.

Peak and Time to Peak Axial Acceleration. Peak acceleration and time to peak axial acceleration as basic axial translational discrete metrics were proposed in paper 6. Data for the 1g are the primary interest over the operating Mach range. The metrics are expressed as:

$$a_x = \frac{G}{V}\,(P_s - dh/dt),$$ where $a_x$ is the axial acceleration

$t_{pk}$ is the time to the peak $a_x$

A complete presentation example used by NASA which would include all possible load factors. Acceleration and deceleration data are the level flight component of the specific excess power formulation. The US Navy method for Ps presentation in terms of kts/sec provides a practical means for characterizing axial acceleration. The time to peak acceleration/deceleration provide insight into the effects of configuration.

Time to Peak Ps. Time to peak specific excess power (Ps) as an axial discrete metric was proposed in paper 6. See 2.1 for a slightly more detailed description of Ps. This metric is expressed as:

$t_{pk}$ Ps is the time to peak Ps

The presentation illustrates the time from initial trim Mach number to the peak Ps. Only the 1g case is significant for pure axial translation.

Power Rate. Papers 6, 10, and 21 proposed power rate (PR) determined from acceleration or deceleration data. The PR is the difference between the initial Ps and final Ps at a given Mach number and altitude divided by the time to transition between the two states. For the acceleration case, the power rate is referred to as the power onset rate and for deceleration, power loss rate. The PR is expressed as:

$$PR = \frac{\Delta P_s}{\Delta t} = \frac{P_{sf} - P_{si}}{t_f - t_i}$$

where $P_{sf}$ is the final Ps at time $t_f$
$P_{si}$ is the initial Ps at time $t_i$

At 1g conditions, a typical presentation of power onset and power loss at various mach numbers and altitudes would be PR versus Mach. This characteristic presents the effects of engine spool up/down and speed brakes on changes is Ps. Elevated normal load factor onset rates would be classified as flight path bending such that a complete presentation is shown in Figure 2.2.4.

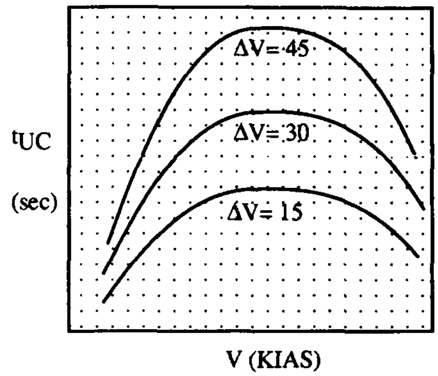
Altitude Capture Time. This metric would measure the time to transition between two altitudes. This metric is expressed as:

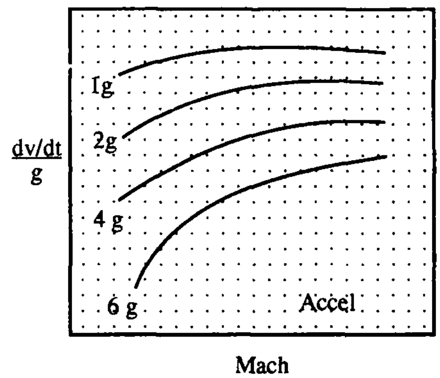
$$t_{\Delta H} = t_{Hf} - t_{Hi} \qquad \text{where} \quad t_{Hf} \text{ is the time at final altitude}$$
$$t_{Hi} \text{ is the time at start altitude}$$

Most likely this metric would be applicable to the rotary wing case from a low to high (or vice versa) hover. This metric is referred to as the altitude time constant in ADS-33C.(28) This metric would depend on the gross weight and climb performance.

Other Translational Metrics. A complete set of translational metrics would characterize the peak and time to peak rates and accelerations in the vertical and sidewards axes. The usefulness of these metrics is unknown at this point but would be primarily of interest for rotary wing and perhaps VTOL agility studies. Mission related metrics could include many other "time to" change translational states and are discussed in 2.2.5. These would be defined by the mission with clear initial and final conditions.

Figure 2.2.4 Translational Agility Metrics.

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{UC}$ | Airspeed Capture Time | Altitude<br>Power Change<br>Configuration<br>Gross Weight |  |
| **Units** | **Source(s)** | | |
| sec | nil | | |
| **Attribute(s)** | | | |
| A,C | | | |

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $a_{x\ pk}$ | Peak Axial Acceleration | Nz<br>Acceleration<br>Deceleration<br>Configuration<br>Secondary<br>Control<br>Position<br>Change |  |
| **Units** | **Source(s)** | | |
| $ft/sec^2$ | NASA (6) | | |
| **Attribute(s)** | | | |
| A,B1,B2,B3,D | | | |

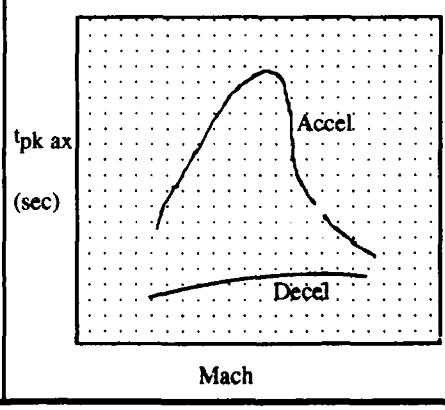
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{pk\ ax}$ | Time to Peak Axial Acceleration | Nz<br>Acceleratio.ı<br>Deceleration<br>Configuration<br>Secondary<br>Control<br>Position<br>Change |  |
| **Units** | **Source(s)** | | |
| sec | NASA (6) | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.4 Continued.

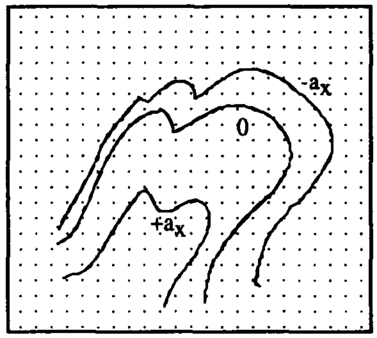
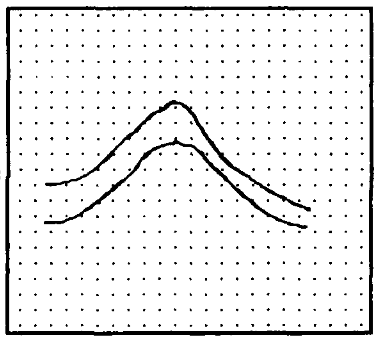
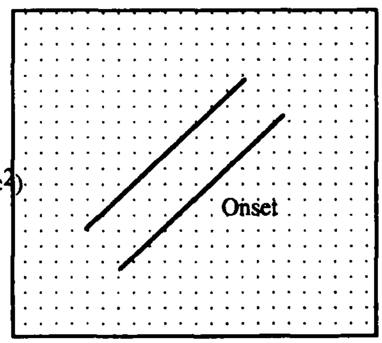
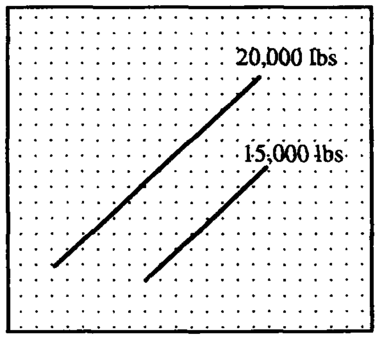
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $a_x$ | Axial Acceleration | Nz<br>Configuration<br>Gross Weight<br>Power Setting | H<br>(ft)<br><br><br>Mach |
| **Units** | **Source(s)** | | |
| kts/sec | US Navy<br>Multiple Others | | |
| **Attribute(s)** | | | |
| A,B1,B2,B3,D | | | |
| **Symbol** | **Title** | **Variables** | **Simplified Plot** |
| $t_{pk}$ Ps | Time to Peak Ps | Nz<br>Configuration<br>Gross Weight<br>Power Setting | $t_{pk}$ Ps<br><br>Mach |
| **Units** | **Source(s)** | | |
| sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |
| **Symbol** | **Title** | **Variables** | **Simplified Plot** |
| PR | Power Rate | Altitude<br>Configuration<br>Power Setting<br>Gross Weight | PR<br>($ft/sec^2$)<br><br><br>Mach |
| **Units** | **Source(s)** | | |
| $ft/sec^2$ | Univ of Kansas<br>Eidetics<br>NASA | | |
| **Attribute(s)** | | | |
| B1,C | | | |

Figure 2.2.4 Continued

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\Delta H}$ | Altitude Capture Time | Altitude<br>Configuration<br>Power Setting<br>Gross Weight | $t_{\Delta H}$ (sec)   H (ft) |
| **Units** | **Source(s)** | | |
| sec | ADS-33C | | |
| **Attribute(s)** | | | |
| A,C | | | |

2.2.4.3 Nose Pointing Metrics

Great interest has recently been generated to focus on the ability of an aircraft to point the nose at an opponent quickly. What is not clear though is the behavior of the flight path during a tactical engagement. Is the nose pointing with respect to the velocity vector or does it include flight path bending or perhaps both? During experimentation, this could be an important issue stemming from various operationally representative scenarios and perhaps more importantly from an operational agility view point determine effective weapons employment. The nose pointing experimental metrics include those metrics which focus on transient changes of body x axis orientation with respect to both the earth and wind axis systems. These changes generally occur at the transition points during a maneuver as the various control inputs are applied by the pilot.

Three possible cases are conceivable that demand different reference systems. The cases are:

1) wind axis nose pointing while maintaining the flight path in the same orientation as it was before the pointing was commenced (linear flight path);
2) nose pointing while bending the flight path; or
3) a combination of one and two.

The first case for nose pointing then is for a flight path that is essentially straight. In other words the nose is displaced with respect to the velocity vector while the center of gravity translates in a linear sense. The most meaningful axis system for this is the wind axis system in order to characterize the changes in angle of attack ($\alpha$) and sideslip ($\beta$) or simply changes of the wind axis with respect to the body axis. The translating center of gravity will assist the experimenter to isolate effects that are angle of attack or sideslip dependant. A significant case for rotary wing occurs when large changes in sideslip are made while maintaining the flight path in the same direction.

The second case is where the flight path also changes or is bent with no change to the wind axis with respect to the body axis. The inertial coordinate system is used or more specifically the changes of the inertial coordinates, pitch ($\theta$), roll ($\phi$), and heading angles ($\psi$), as the nose is pointed. The inertial reference frame is perhaps more tactically significant when orientation with respect to an adversary must be considered. Isolating changes to only the body axis with respect to the inertial frame might be difficult for fixed wing aircraft because as the flight path is bent changes do occur in the wind axis. An important point to make though is that the angle of attack or sideslip is not necessarily zero and is ignored providing it is held within safe limits, such as at high speed conditions when load factor limits are reached first.

The third case is perhaps the most realistic in that differences between the body and wind axes will occur during flight path bending. This is the case now with most tactical fixed wing aircraft depending on whether the airspeed is fast or slow. Changes in both reference systems could be dominated by longer term changes in the one reference system with short term changes in the other. This is especially the case for a maneuver where the airspeed decreases during the maneuver. An example of this might be the horizontal turn started from wings level flight where several different sequences of events could transpire including: roll into, pull, unload, roll level, or roll and pull, rollout and unload. If held long enough, the change in the wind axis with respect to the body axis may start low and increase as airspeed is bled away. Through flight simulations, NASA researchers identified the different behavior in the wind and body pitch axes of a fixed wing aircraft and are discussed in paper 6. Murphy etal noted that longitudinal stick displacements would be expected to command the flight path in addition to the aircraft nose pointing pitch angle for agile aircraft. The study points out that current aircraft behave differently in the high speed and slow speed regimes. In the high speed case the flight path displaces as per the nose pointing displacement. (6) The low speed case exhibits no flight path or even opposite flight path displacements. Murphy etal remarked that improved controllability over a wide AOA range could enhance control of both the flight path angle. This characteristic ultimately links nose pointing metrics to flight path control metrics.

One other complicating factor which is introduced when the inertial reference frame is used is the effect of gravity during vertical, horizontal, or combined vertical/horizontal motions. Murphy also suggested in paper 6 that, nose pointing could be characterized as pure vertical and horizontal motions. Using this method, the vertical motions would characterize the pitch and horizontal motions mainly pitch but including roll. The latter roll effects would

depend on the initial conditions.

To avoid confusion, the metrics will be presented here in the reference frame from which they have originated. The organization of which will be left up to the user. This subject should be the basis for further study and clarification.

Angle of Attack Capture Time. This metric measures the time to transition from an initial to a final angle of attack. The metric is expressed as:

$$t_{\Delta\alpha} = t_{\alpha f} - t_{\alpha i} \quad \text{where} \quad t_f \text{ is the final angle of attack, and} \quad t_i \text{ is the initial angle of attack.}$$

Murphy suggested the presentation shown in Figure 2.2.5. This metric could be divided into the slow speed and high speed regimes. The slow airspeed case will isolate large changes of the body x axis with respect to the velocity vector. Higher airspeeds will tend have lower angles of attack limited by the structural limits of the aircraft.

Angle of Attack Pointing Envelope. This metric characterizes the complete envelope of angle of attack for an aircraft. Murphy etal suggested that the ability to displace the nose relative to the velocity vector on command could be a desirable agility characteristic. (6) The most efficient method for presenting this data was the angle of attack pointing envelope shown in Figure 2.2.5. On this presentation the trim AOA, maximum up/down AOA, and maximum AOA change in 1 second metrics can be presented simultaneously.

Peak and Time to Peak Angle of Attack Rate. This metric characterizes the peak and time to peak angle of attack rates achievable by the aircraft. Presentations are shown in Figure 2.2.5. The presentation of AOA rate shows that for the conventional aircraft, higher angle of attack rates are achievable at lower mach numbers.

Angle of Sideslip Capture Time. This metric measures the time to transition from an initial and final angle of sideslip. The peak and time to peak yaw angle was assessed by students at the USAF Test Pilot School and reported on in paper 29. A complete data presentation was not available as angle of sideslip is generally not of primary interest for nose pointing with current fixed wing aircraft. The format would likely be similar to Figure 2.2.5. One other presentation format that does not include time but identifies the relationship between peak sideslip and airspeed may be found in paper 11 as presented by other researchers at the AFFTC. Future work would be beneficial for this metric. Ref 25 discusses rotary wing data which exceeds the capability of current generation helicopter during various sideslip change maneuvers.

Angle of Sideslip Pointing Envelope. As for angle of attack pointing, an angle of sideslip pointing envelope could be defined with an aircraft with a wide range of possible sideslips. A similar envelope as was used for AOA pointing envelope would be suitable. Left to right asymmetries could be identified. In all likelihood, the angle of sideslip pointing envelope would be expected to be much narrower than the angle of attack envelope. It would only be pre-stall angle of sideslip. Actual aiming in sideslip may also be automated. Future work would be beneficial in this metric.

Other Wind Axis Metrics. Other metrics which are conceivable include: angles of attack acceleration, sideslip rates, and sideslip accelerations. With the advent of thrust vectoring and post stall maneuvering the importance of separating the ability to displace the nose with respect to the velocity vector as opposed to bending the flight path will grow.

Pitch Angle Capture Time (pure vertical). The metric measures the time to transition from an initial to final pitch angle. The metric is expressed as:

$$t_{\Delta\theta} = t_{\theta f} - t_{\theta i} \quad \text{where} \quad t_{\theta f} \text{ is the time at the final pitch angle, and} \quad t_{\theta i} \text{ is the time at the initial pitch angle.}$$

This data can be presented as shown in Figure 2.2.5. From the data studied in reference 6, Murphy concluded that

the best nose-up pointing generally occurred at the corner speed and best nose-down occurred below corner speed. Murphy suggested that improved agile performance in pitch may be obtained from pitch change in proportion to stick deflection. It is important to note that changes in pitch angle ($\theta$) are in the vertical orientation only as the local horizontal is defined as $\Delta\theta = 0^{o}$. Extensive flight test data were presented in reference 1.

Pitch Angle Pointing Envelope (pure vertical). A more comprehensive presentation of the pitch pointing capabilities was suggested by Murphy to be the pitch angle pointing envelope. This envelope is shown in Figure 2.2.5. This plot also shows data for the trim pitch angle, the maximum up/down displacements, and could include $\Delta\theta$ in one second metrics.

Peak and Time to Peak Pitch Rates. These metrics measure the time to reach the peak pitch rate and what pitch rate is available. Pitch rates in both the body (Q) and wind ($Q_w$) axis systems as metrics for pitch motion agility were proposed in paper 6. The separation of the response between the body and wind axes can illustrate the difference in control over the operating Mach range for typical fighters. Figure 2.2.5 shows time to peak pitch rate data. Murphy etal observed that below corner speed the time to peak pitch rate was slow. Also the time for wind axis peak pitch rate grows to a point were there is virtually no flight path control for slow speed flight. Murphy etal also noted that the pitch down rates were low. Since these five metrics do not use an inertial frame, data for non-vertical motions are also possible. Presentations in Figures 2.2.5 are for pure vertical motion. Pitch rate can also be measured in the inertial frame as the pitch angle rate ($d\theta/dt$). As of yet no meaningful pitch angle rate data has been gathered or used.

Pitch Quickness Parameter (Pure Vertical). The pitch angle and peak pitch rate data have been combined successfully to obtain perhaps one of the most important pitch agility metrics the pitch attitude quickness parameter.(28) This metric is expressed as:

$$\text{Pitch Quickness Parameter} = \frac{Q_{pk}}{\Delta\theta}$$

where $Q_{pk}$ *is the peak pitch rate,*
and $\theta\Delta$ is the pitch angle change.

This data is presented versus the minimum angular change around the axis of interest. This data has been gathered for rotary wing aircraft, although more so for the roll attitude parameter. Figure 2.2.5 shows PQP data correlated with handling qualities data. The data has been correlated with flying qualities levels for acceptability indicated potential bounds on agility. More fixed wing research needs to be performed on this subject.

Peak and Time to Peak Pitch Accelerations (Pure Vertical). Paper 6 proposed pitch accelerations in the body and wind axis systems as the primary metrics for pitch motion agility. An example presentation of peak acceleration data is shown in Figure 2.2.5. Interestingly, the data for the peak accelerations for the body and peak axes show differences. This effect has implications on control scheme as pointed out by Murphy etal. The report suggested that future designs may require pilot selection of flight path or nose pointing control during maneuvering. The time to peak acceleration provides insight into the jerk characteristics of pitch motion. An example presentation is shown in Figure 2.2.5. Alternately, the AFFTC presented pitch acceleration data versus angle of attack.

Load Factor Capture Time. This metric measures the time to transition from an initial to a final load factor at a single Mach number. The metric is expressed as:

$$t_{\Delta Nz} = t_{Nzf} - t_{Nzi}$$

where $t_{Nzf}$ is the time when the final load factor is reached, and
$t_{Nzi}$ is the time when the initial load factor was changed.

This metric should be presented for time to pitch up to a target load factor and time to pitch back down, usually to

0g. The AFFTC data presentation format is shown in Figure 2.2.5. AFFTC present data in paper 1 for transitions between various load factors. Data were gathered in both vertical and horizontal motions.

Peak and Time to Peak Normal Load Factor. For optimum flight path bending, these metrics describe the peak and transition time to the peak normal load factor. It was suggested in paper 6 that the wind axis load factor approximates the flight path bending capability of an aircraft. An example presentation is shown in Figure 2.2.5. Murphy etal noted that this figure illustrated the deficiency in many current aircraft to slowly unload which corroborated Skow's observations.(10) Data were also presented in paper 21 for complete mach and altitude effects. The author's of this paper pointed out that the time to reach the peak load factor may be misleading under some circumstances if the attainable peak load factor changes as mach number is increased.

Maximum Load Factor Rates. The maximum g-onset rate attainable has also been suggested as a metric. Again this data should be presented for loading and unloading. The affect of altitude and Mach number is illustrated in Figure 2.2.5.(21) The AFFTC presented the maximum load factor rates versus angle of attack.(1) Theses data could be gathered for both vertical and horizontal motions.

Changes in Specific Excess Power For Pitch (Pure Vertical). Murphy etal suggested a number of specific excess power metrics to characterize the energy efficiency of the aircraft in pure vertical maneuvers. These metrics were the: peak change in Ps and peak Ps rate. The peak change in Ps was calculated as the difference between the peak Ps and the initial Ps. The presentation scheme used by NASA is shown in Figure 2.2.5. Murphy noted that this shows the cost in Ps as airspeed is increased indicating the availability of greater control power. (6) The peak Ps rate shown in Figure 2.2.5 shows the efficiency of a maneuver. (6).

Time to Change Heading Angle (Pure Horizontal). For nose pointing maneuvers in the horizontal plane, the heading angle is generally used to characterize the achievable angular change. This metric is expressed as:

$$t_{\Delta\psi} = t_{\psi f} - t_{\psi i}$$

where $t_{\psi f}$ is the time at final heading angle,
and $t_{\psi i}$ is the time at initial heading angle.

As an example presentation the AFFTC format is shown in Figure 2.2.5. Interestingly, the post-stall case has undergone some investigation. The USAF TPS undertook a study of a metric which was referred to as the angular reserve, or the maximum heading change an aircraft could generate before slowing to a turn rate equal to or less than the maxim n pre-stall turn rate. Data for the angular reserve may be found in paper 24.

Heading Angle Rate (Pure Horizontal). Murphy etal suggested that instantaneous body axis turn rate in a horizontal turn permit optimization of rapid nose pointing to achieve a first shot. (6) The instantaneous wind axis turn rate was suggested to optimize rapid flight path changes in such situations as rapid evasive maneuvering. (6) Differences in the wind and body axes turn rates over a range of mach numbers are shown in Figure 2.2.5.

Power Rate. The power rate was first introduced in 2.2.4.2 as a translational metric for the 1g case. The complete presentation should include the full flight path bending capabilities of the aircraft. Furthermore, the ability to accelerate or decelerate while bending the flight path are meaningful information. Data could be illustrated as shown in Figure 2.2.5 a format suggested by Skow.(23) This parameter will be very important for presenting the energy cost of rapid nose pointing. It will also be useful for demonstrating the worth of new technologies such as thrust vectoring.

Other Nose Pointing Metrics. For maneuvering in the horizontal plane, rolling maneuvers are also required to tilt the lift vector. This aspect of the nose pointing metrics have been avoided since the roll is required for setup. The time to achieve the heading angle change if started and stopped at a wings level conditions would, however, include a roll. The approach in this study was to define experimental metrics that are short time slices of a more complex maneuver so that the response in each degree of freedom could be more easily isolated.

The addition of post-stall data would be beneficial for a complete understanding of low speed nose pointing.

Definition by the USAF TPS of the angular reserve concept demonstrated that valuable metrics are still to be defined for the expanded flight envelope.

Finally, several other attitude quickness parameters may be defined for the wind axis system as well as isolated to pure vertical and horizontal maneuvers. These parameters would be expressed as:

Angle of Attack Quickness Parameter: $\alpha QP = \dfrac{Q_{Pk\,w}}{\Delta\alpha}$

Angle of Sideslip Quickness Parameter: $\beta QP = \dfrac{R_{Pk\,w}}{\Delta\beta}$

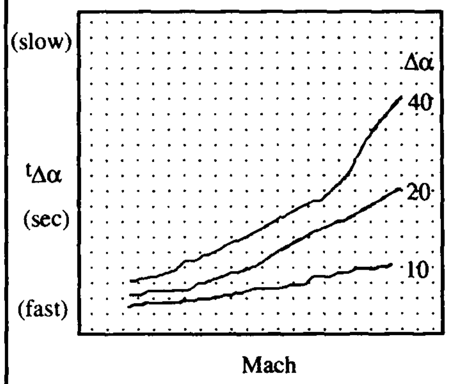
Pure Vertical Pitch Quickness Parameter: $PQP_v = \dfrac{Q_{pk}}{\Delta\theta}$

Pure Horizontal Pitch Quickness Parameter: $PQP_H = \dfrac{Q_{pk}}{\Delta\psi}$

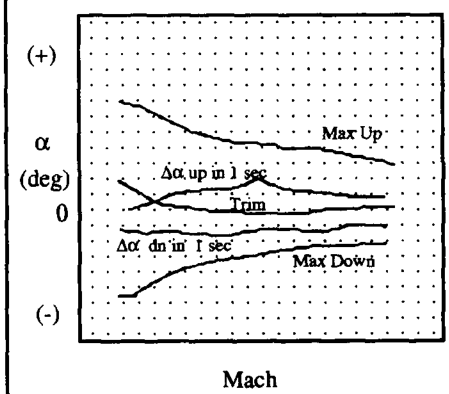
Heading Angle Quickness Parameter: $HQP = \dfrac{R_{pk}}{\Delta\psi}$

These metrics reflect the need to clearly the reference systems used to characterize nose pointing because one version is with respect to the body axis and the other possible with respect to the velocity vector.

Figure 2.2.5 Nose Pointing Agility Metrics

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\Delta\alpha}$ | Angle of Attack Capture Time | Initial AOA<br>Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| sec | NASA<br>AFFTC | | |
| **Attribute(s)** | | | |
| A,B1,B2,C | | | |



| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| - | Angle of Attack Pointing Envelope | Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| deg | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |



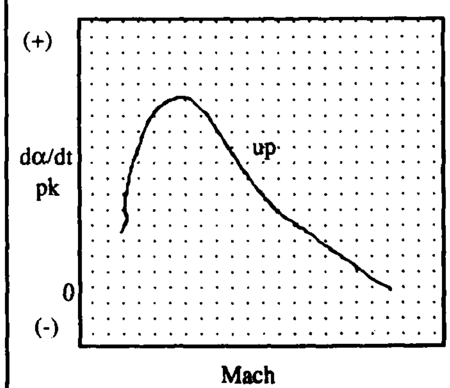
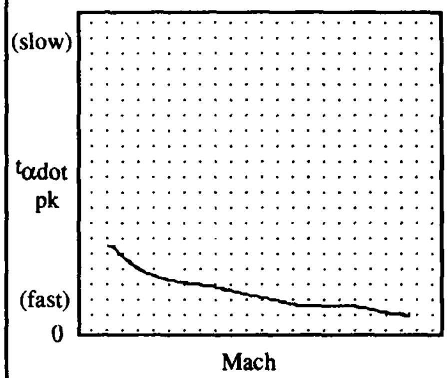
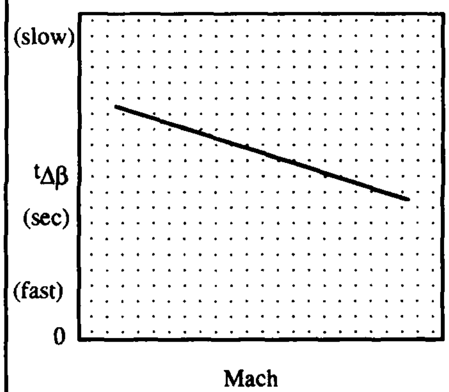
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| dα/dt pk | Peak Angle of Attack Rate | Initial AOA<br>Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| deg/sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.5 Continued.

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\dot{\alpha} pk}$ | Time to Peak Angle of Attack Rate | Configuration Gross Weight Center of Gravity |  |
| **Units** | **Source(s)** | | |
| sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |



| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\Delta\beta}$ | Angle of Sideslip Capture Time | Initial AOS Configuration |  |
| **Units** | **Source(s)** | | |
| sec | AFFTC NASA | | |
| **Attribute(s)** | | | |
| A,B1,B2,C | | | |



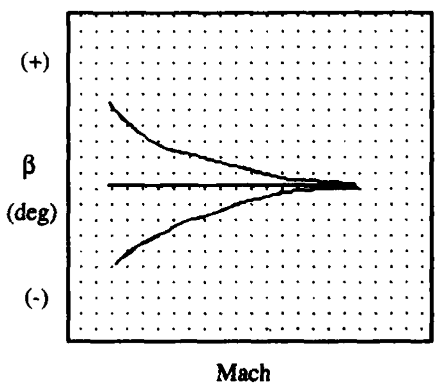
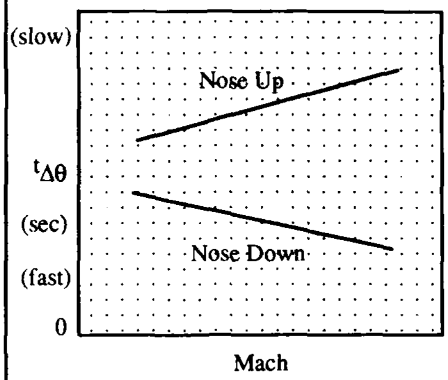
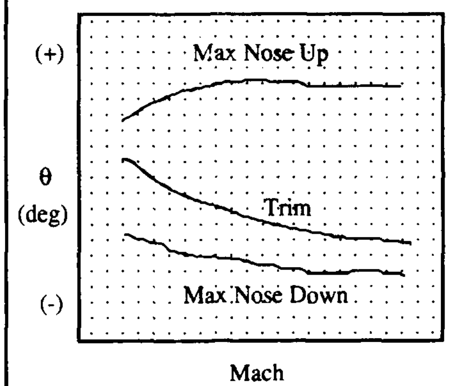
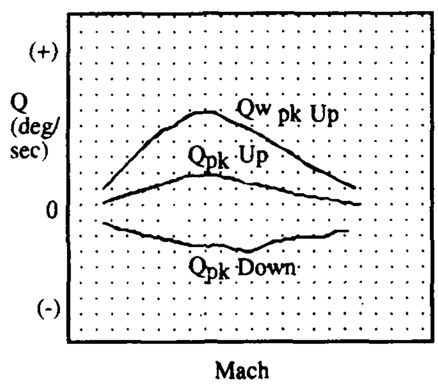
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| - | Angle of Sideslip Pointing Envelope | Configuration |  |
| **Units** | **Source(s)** | | |
| deg | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.5 Continued

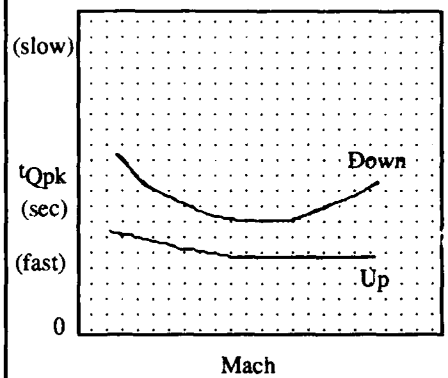
<table>
<tr><th>Symbol</th><th>Title</th><th>Variables</th><th>Simplified Plot</th></tr>
<tr><td>$t_{\Delta\theta}$</td><td>Time to Change Pitch Angle</td><td rowspan="5">Configuration<br>Gross Weight<br>Center of Gravity</td><td rowspan="5">


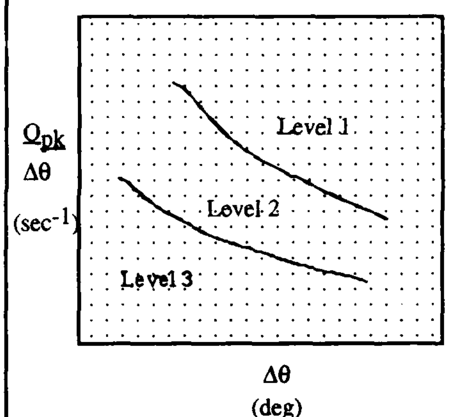
</td></tr>
<tr><td>Units</td><td>Source(s)</td></tr>
<tr><td>sec</td><td>NASA<br>AFFTC</td></tr>
<tr><td colspan="2">Attribute(s)</td></tr>
<tr><td colspan="2">A,B1,B2,C</td></tr>
<tr><th>Symbol</th><th>Title</th><th>Variables</th><th>Simplified Plot</th></tr>
<tr><td>-</td><td>Pitch Angle Pointing Envelope</td><td rowspan="5">Configuration<br>Gross Weight<br>Center of Gravity</td><td rowspan="5">


</td></tr>
<tr><td>Units</td><td>Source(s)</td></tr>
<tr><td>deg</td><td>NASA</td></tr>
<tr><td colspan="2">Attribute(s)</td></tr>
<tr><td colspan="2">A,B1,D</td></tr>
<tr><th>Symbol</th><th>Title</th><th>Variables</th><th>Simplified Plot</th></tr>
<tr><td>$Q_{pk}$<br><br>$Qw_{pk}$</td><td>Body Axis Pitch Rate<br><br>Wind Axis Pitch Rate</td><td rowspan="5">Configuration<br>Gross Weight<br>Center of Gravity</td><td rowspan="5">


</td></tr>
<tr><td>Units</td><td>Source(s)</td></tr>
<tr><td>deg/sec</td><td>NASA</td></tr>
<tr><td colspan="2">Attribute(s)</td></tr>
<tr><td colspan="2">A,B1,D</td></tr>
</table>

*Figure 2.2.5 Continued.*

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{Qpk}$ | Time to Peak Pitch Rate | Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $\frac{Q_{pk}}{\Delta\theta}$ | Pitch Rate Attitude Quickness Parameter | Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| $sec^{-1}$ | ADS-33C | | |
| **Attribute(s)** | | | |
| A,B1,C | | | |

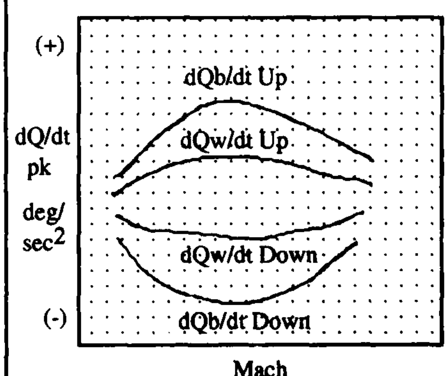
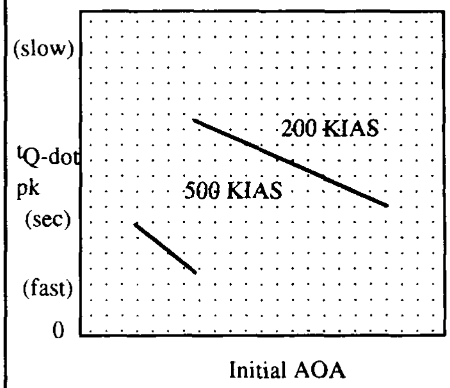
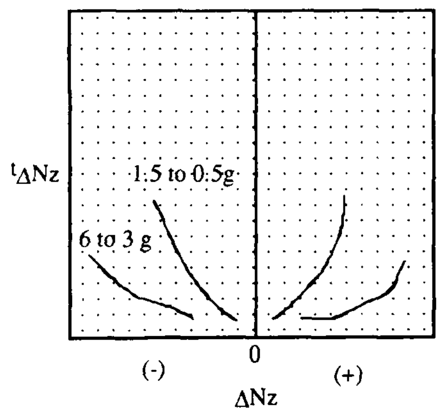
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| dQ/dt pk | Peak Pitch Angle Acceleration | Configuration<br>Gross Weight<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| deg/ $sec^2$ | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.5 Continued.

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\dot{Q}pk}$ (tQ-dot pk) | Time to Peak Pitch Angle Acceleration | Altitude<br>Gross Weight<br>Bank Angle<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| sec | AFFTC<br>NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |



| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\Delta Nz}$ | Time to Capture Load Factor | Altitude<br>Gross Weight<br>Bank Angle<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| sec | AFFTC<br>NASA | | |
| **Attribute(s)** | | | |
| A,B1,B2,C | | | |



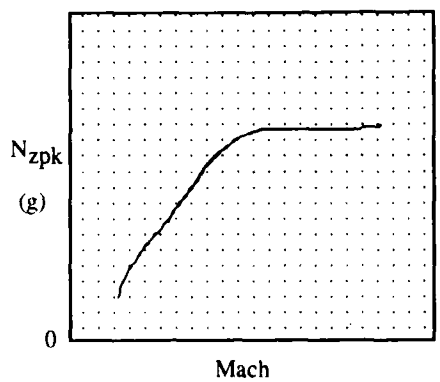
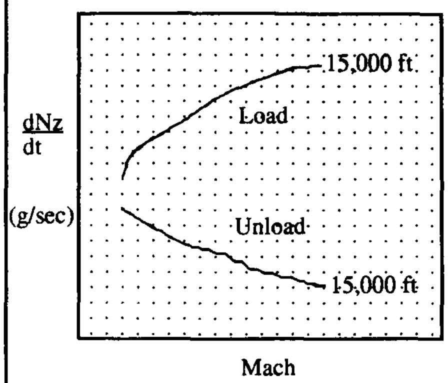
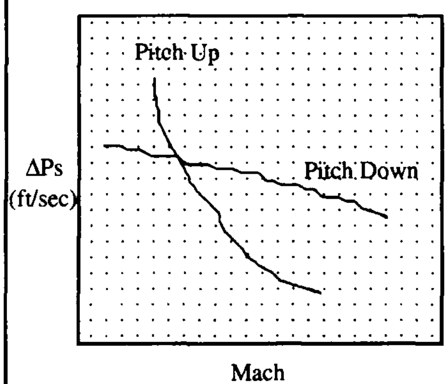
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $N_{zpk}$ | Peak Normal Load Factor | Altitude<br>Gross Weight<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| g | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.5 Continued.

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $\frac{dNz}{dt}$ | Maximum Load Factor Rate | Altitude<br>Gross Weight<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| g/sec | NASA<br>Univ of Kansas | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $\Delta Ps$ | Peak Change in Ps | Altitude<br>Gross Weight<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| ft/sec | NASA | | |
| **Attribute(s)** | | | |
| A,D | | | |

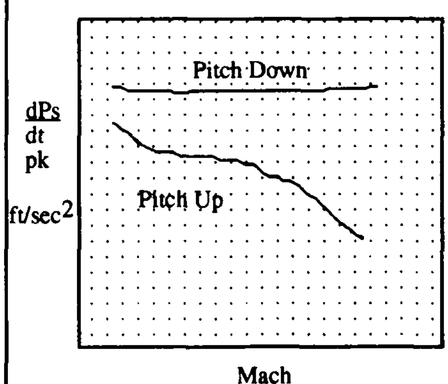
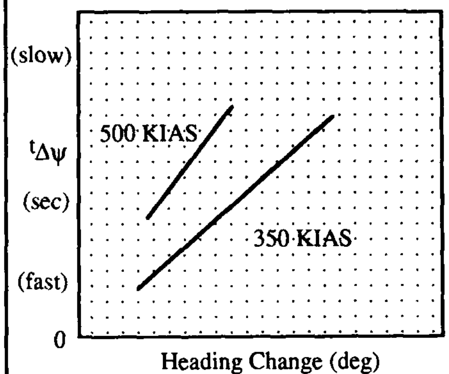
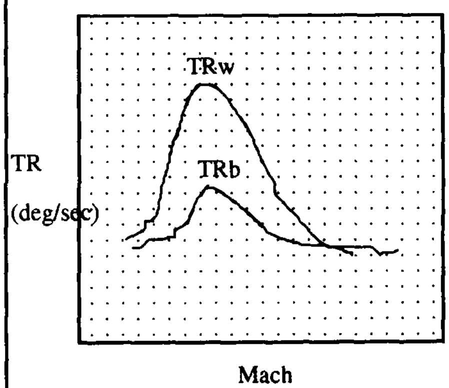
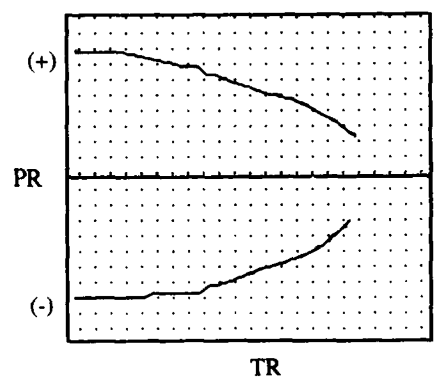
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $\frac{dPs}{dt}$ pk | Peak Ps Rate | Altitude<br>Gross Weight<br>Configuration<br>Center of Gravity |  |
| **Units** | **Source(s)** | | |
| $ft/sec^2$ | NASA | | |
| **Attribute(s)** | | | |
| A,B1,B2 | | | |

Figure 2.2.5 Continued

| Symbol | Title | Units | Source(s) | Attribute(s) | Variables | Simplified Plot |
|---|---|---|---|---|---|---|
| $t_{\Delta\psi}$ | Time to Change Heading Angle | sec | AFFTC<br>NASA | A,B1,C | Altitude<br>Bank Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |  |
| TR | Instantaneous Turn Rates<br>(Angular Reserve) | deg/sec | NASA<br>AFFTC | A,B1,B2,C | Altitude<br>Bank Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |  |
| PR | Power Rate | $\frac{deg}{sec^2}$ | Eidetics<br>NASA | A,B1 | Altitude<br>Bank Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |  |

2.2.4.4 Torsional Metrics

The final grouping of experimental metrics are the torsional metrics. This group characterizes those motions involving rotation of the lift vector. Although not a direct capability to engage an opponent, torsional motions are necessary to re-orient the lift vector so as to nose point. Rotations of the lift vector can be described by a rotation about the velocity vector in the wind axis system or with respect to an inertial frame as a change in roll angle ($\phi$). Body axis rolls at moderate to high angles of attack are not of great interest because of the risk of inertial coupling. The torsional metrics are listed in Figure 2.2.6.

Time to Capture a Roll Angle. This metric details the time required to roll through a prescribed roll angle. The metric is expressed as:

$$t_{\Delta\phi} = t_{\phi f} - t_{\phi i}$$

where $t_{\phi f}$ is the time at final roll angle,
and $t_{\phi i}$ is the time at the initial roll angle.

Data may be presented as shown in Figure 2.2.6 for a 90 degree roll angle change at various angles of attack and mach numbers. Other formats show the data for a range of roll angle changes but at one load factor and altitude.

Peak and Time to Peak Wind-Axis Roll Rate. This metric describes the capability for an aircraft to reach its peak roll rate. For completeness the data should be presented for various load factors. At a given altitude the peak and time to peak roll rate can be presented as shown in Figure 2.2.6. This presentation shows regimes where control power is reduced.

Roll Rate Normal Load Factor Product (PN). Murphy etal suggested one other method for simultaneously presenting the wind axis roll rate under loaded conditions is the PN metric. (6) This metric is calculated by:

$$PN = p_w N_{z,w} \qquad \text{(deg-g/sec)}$$

Murphy etal noted that this metric reflects the desire to rotate the aircraft about the velocity vector while simultaneously rotating the flight path. Figure 2.2.6 shows a family of curves for various load factors. The experimental agility metric in this case may better be defined as the peak PN value.

Roll Quickness Parameter. This metric combines the roll angle and peak roll rate metric data. The metric is expressed as:

$$\text{Roll Quickness Parameter} = \frac{P_{pk}}{\Delta\phi}$$

where $P_{pk}$ is the peak roll rate,
and $\Delta\phi$ is the roll angle change.

An example presentation is shown in Figure 2.2.6. As for the pitch quickness parameter, the approach permits the definition of bounds imposed by handling qualities.

Reference 2 concluded that the Attitude Quickness Parameter has only been supported by rotary wing research and criterion boundaries have not been developed for fixed wing aircraft. Since these parameters are able to link flying qualities levels to the peak angular rates, they do illustrate bounds on agility. Therefore, they could be a very useful ADP. Further research is required to specify desirable peak angular rates for "agile maneuvers". One example of high amplitude criteria aimed at upgrading flying qualities specifications for helicopters but actually in the realm of agility was described in reference 19. The data was gathered by DFVLR and a variable stability BO 105 ATTHeS. The nap-of-the-earth slalom mission task element was flown to assess the peak roll rates and corresponding roll angle change superimposed with proposed flying qualities specification level 1, 2, and 3. One interesting observation from this approach is that the data is actually gathered during operational maneuver segments (see 2.2.5).

Would one approach to mission optimization might be to tailor the response in each axis for aggressive maneuvering in mission related maneuvers. Doing this could bring together the potentially conflicting requirements of flying qualities and agility yet maximizing the mission effectiveness. Much more research is needed in this area, especially for fixed wing missions.

Skow's High Angle of Attack Roll Agility Metrics. Skow suggested several roll axis metrics to characterize the capability of aircraft to point the normal-force vector or to point weapons at an adversary (ref 10). These metrics therefore combine the response of the aircraft in several axes. The normal-force vector is dependant on lift and thrust effects as well as the roll axis. Weapons pointing (fixed longitudinal axis boresight weapons) is dependant on the body roll and yaw capabilities about the center of gravity of the aircraft. Either normal-force vector changes or nose pointing may be used to employ a weapon, however, the characteristics of one may be weak depending on the where in the envelope the aircraft is operating. Therefore both must be considered simultaneously.

The torsional agility (TA) metric attempts to capture the maneuver dynamics and control transient effects associated with the normal-force vector control. The proposed metric was:

$$\text{Torsional Agility} = \frac{\text{Turn Rate}}{\text{Time to roll and capture 90 deg bank}} = \frac{TR}{\Delta t_{RC90}} \quad (\text{deg/sec}^2)$$

Skow points out that low values of TA indicate highly maneuverability but sluggish roll/yaw axis controllability, or high roll rates an low maneuverability. Therefore, Skow suggested that the TA metric can be used to balance high maneuverability and fast roll/yaw transient response. The TA metric generally characterized as shown in figure 2.2.6.

The Lateral Agility (LA) metric was proposed to characterize the capability to point the nose of the aircraft. The LA metric proposed was:

$$\text{Lateral Agility} = \frac{1}{\Delta t_{RC90}} \quad (1/\text{sec})$$

This metric does not depend on the orientation of the normal-force vector. The LA metric data are generally characterized as shown in Figure 2.2.6 versus AOA. The sign of the LA metric is determined by the direction of the roll.

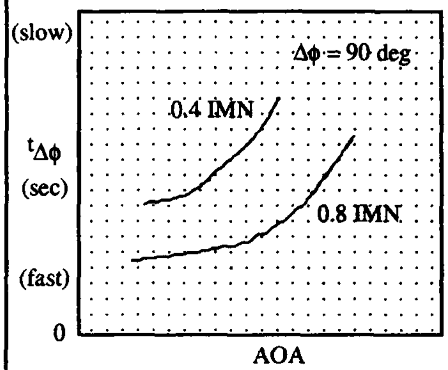
Skow presents some data comparing the TA and LA characteristics of current fighter aircraft in reference 10. Out of interest, Skow also mentioned that a 90 degree roll capture bank angle was selected because in a pilot survey, 30 degrees was felt to be too small a change and 180 degrees was too long.

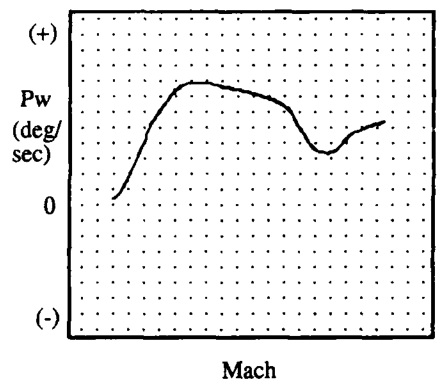
Murphy etal suggested that wind axis roll maneuvers resulting in rotating the aircraft around its velocity vector at all AOAs are the only relevant agility characteristics in torsion. Body axis rolls at low AOA are already characterized by existing flying qualities metrics. Body axis rolls at high AOA are undesirable due to inertial coupling mechanisms.

Peak and Time to Peak Wind Axis Roll Acceleration. Murphy etal summarized the peak and time to peak wind axis roll acceleration in Figure 2.2.6. These figure can be prepared for specific load factors and also shows regimes of weakened control power.

Other Torsional Metrics. No other torsional metrics have been presented in the literature. Torsional agility has been the focus of attention and it would appear that very few other metrics could be expected.

Figure 2.2.6 Torsional Agility Metrics

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{\Delta\phi}$ | Time to Capture Roll Angle | Altitude<br>Direction of Roll<br>Load Factor<br>AOA<br>Roll Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |   |
| **Units** | **Source(s)** | | |
| sec | AFFTC<br>NASA | | |
| **Attribute(s)** | | | |
| A,B1,B2,C | | | |

| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| Pw | Peak Roll Rate | Altitude<br>Bank Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |   |
| **Units** | **Source(s)** | | |
| deg/sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

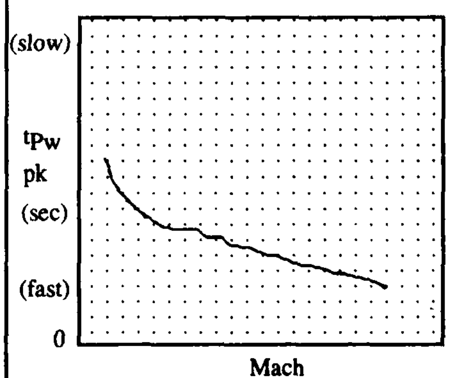
| Symbol | Title | Variables | Simplified Plot |
|---|---|---|---|
| $t_{Pw_{pk}}$ | Time to Peak Wind Axis Roll Rate | Altitude<br>Bank Angle<br>Gross Weight<br>Center of Gravity<br>Configuration |   |
| **Units** | **Source(s)** | | |
| sec | NASA | | |
| **Attribute(s)** | | | |
| A,B1,D | | | |

Figure 2.2.6 Continued.

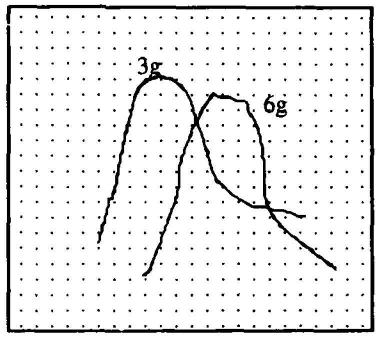
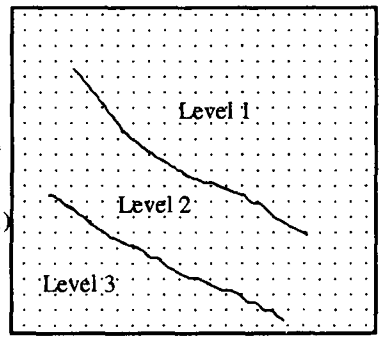
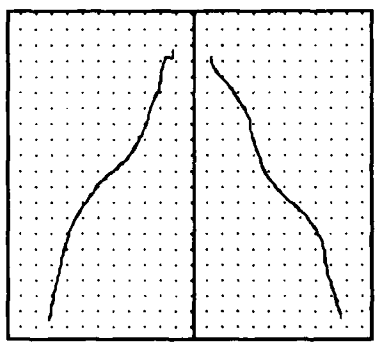
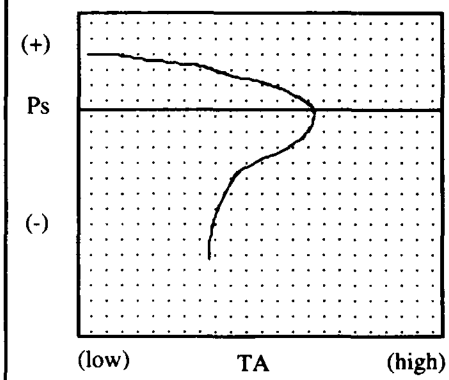
| Symbol | Title | Units | Source(s) | Attribute(s) | Variables | Simplified Plot |
|---|---|---|---|---|---|---|
| PN | Roll Rate Normal Load Factor Product | $\frac{deg\text{-}g}{sec}$ | NASA | A,B1,D | Gross Weight<br>Center of Gravity<br>Configuration | PN   Mach |
| $\frac{P_{pk}}{\Delta\phi}$ | Roll Rate Attitude Quickness Parameter | $sec^{-1}$ | ADS-33C | A,B1,C | Gross Weight<br>Center of Gravity<br>Configuration | $\frac{P_{pk}}{\Delta\phi}$ (sec-1)   $\Delta\phi$ (deg) |
| LA | Lateral Agility | $sec^{-1}$ | Eidetics | A,B1,C | Gross Weight<br>Center of Gravity<br>Configuration | 90 AOA 0  (-) LA ($sec^{-1}$) (+) |

Figure 2.2.6 Continued

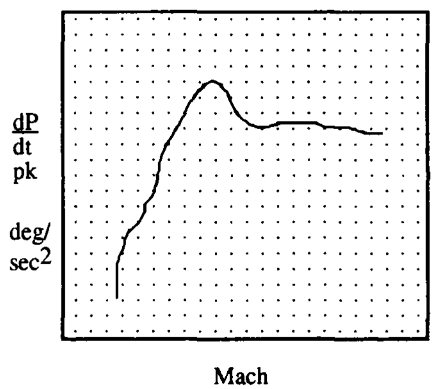
| Symbol | Title | Units | Source(s) | Attribute(s) | Variables |
|---|---|---|---|---|---|
| TA | Torsional Agility | deg/ $sec^2$ | Eidetics | A,B1,C | |

**Simplified Plot**



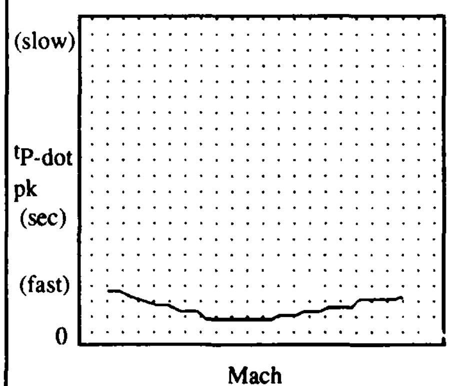

| Symbol | Title | Units | Source(s) | Attribute(s) | Variables |
|---|---|---|---|---|---|
| $\frac{dP}{dt}$ pk | Peak Roll Acceleration | deg/ $sec^2$ | NASA | A,B1,D | Gross Weight<br>Center of Gravity<br>Configuration |

**Simplified Plot**




| Symbol | Title | Units | Source(s) | Attribute(s) | Variables |
|---|---|---|---|---|---|
| $t_{P\text{-dot}}$ pk | Time to Peak Roll Acceleration | sec | NASA | A,B1,D | Gross Weight<br>Center of Gravity<br>Configuration |

**Simplified Plot**



## 2.2.5 Operational Agility Metrics

The operational metrics consider the transient changes of state which occur in realistic combat situations. These metrics characterize the behavior of the aircraft in a more global sense looking at the performance, maneuvering, and man-machine interface aspects of airframe agility. First and foremost, the operational metrics depend on the mission. This extends further than conventional flight mechanic principles and theory. The desired results obtained from the operational metrics would be detailed in a specification and may be traded off to other more critical performance measures.

Operational metrics have two main aims: mission task quickness and mission task precision. Both of these stem from the airframe agility definition. The mission task quickness is best characterized as a "time to perform a task".

The mission task precision depends largely on the purpose of the task. Examples of precision tasks are: engagement, AAR drogue contact, landing, and NOE maneuvering. The engagement task precision may be defined by a weapons system accuracy requirement. To analyze the operational metrics available metrics may be classified as global or specific to a mission.

### 2.2.5.1 Global Operational Agility Metrics

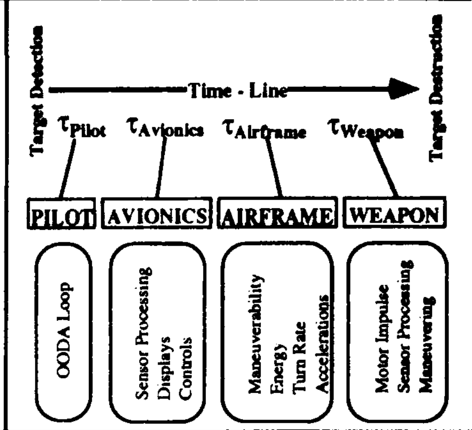
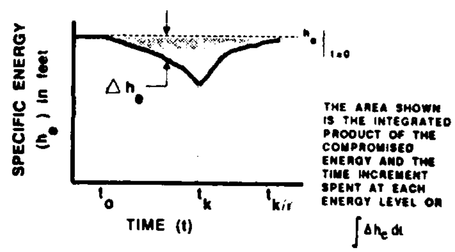
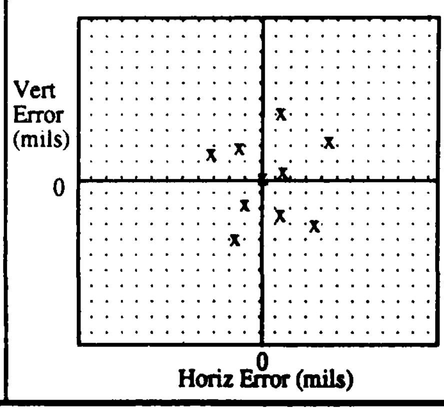
The global operational agility metrics characterize the overall airframe agility in a top-down sense for a mission task. These metrics are not aircraft type dependant. These metrics are illustrated in Figure 2.2.7.

Time to perform a Task. The time to perform specific mission tasks to study agility was first proposed by Skow in reference 10. This approach to a time-line for a mission profile sequence provided a means with which to determine what components of an aircraft weapon system contributed large "time delays" to an engagement. The time-line is illustrated in Figure 2.2.7. Poor agility could therefore be viewed as a result of excessive "time to" perform critical tasks. Therefore, the time to perform a task could be viewed as the most basic measure of airframe operational agility. This characteristics also has the benefit of being applicable to any task and therefore any mission so it can be viewed as a global agility metric. The experimental metrics provided some of the individual "time to" data but does not provide all the delays associated with a mission task. The overall time to perform a task includes delays due to: the operator, pilot-vehicle interface, flight control system, airframe, and engine. The symbol $\tau$ is common for time delay. Therefore, time to complete a MTE could be expressed as: $\tau_{MTE}$ ; eg.$\tau_{LCH}$ is the time to launch a missile.

Dorn's Energy-Agility Metric. Dorn proposed a metric for weighing the energy lost during a complete engagement segment (7). In his example, illustrated in Figure 2.2.7, the energy agility would be the area of the curve from commencement of the engagement to recovery back to initial energy conditions. Dorn suggested that in a target rich environment loss of significant energy would be a vulnerability and therefore the loss of area should be minimized. This metric could easily be adapted to any mission task and could be used to weight magnitude change of state condition with that of the energy expended.

Accuracy Metrics. Existing accuracy metrics are suitable for characterizing the aiming accuracy during or after an agile maneuver. The vertical and horizontal aiming error in mils for a tracked airborne target or a cross range and down range error for ground targets are the metrics. Specific tolerances will be defined by a particular weapon system or the user. A typical plot is shown in Figure 2.2.7. This format is useful for calculating Circular Error Probable (CEP) and other useful operational effective measures.

Figure 2.2.7 Global Agility Metrics

| Symbol | Title | Units | Source(s) | Attribute(s) | Variables | Simplified Plot |
|---|---|---|---|---|---|---|
| τ | Time to Perform a MTE | sec | Eidetics | A,B1,C | Mission Task Variables |  |
| E-A | Energy Agility | - | Dorn | A,C,D | Mission Task<br>Configuration<br>Gross Weight<br>Power Setting |  |
| - | Aiming Error | mils | Multiple | A,B3,C | Mission Task<br>Configuration |  |

Aggressiveness Rating. The Handling Qualities Rating (HQR) has been successfully used to characterize the compensation required to correct for poor flying qualities for *precision tasks*. No rating system has been prepared for *moderate or large amplitude maneuvers*. For agility evaluations, an aggressiveness rating system is thought to be useful. The requirement stems from the difficulty in determining a maximum performance boundary which is normally defined by handling qualities cliffs (eg. departure limits), structural, and physiological limits.

The purpose of such a rating would be to describe qualitatively, the aggressiveness of a pilot in performing a task. Repeatability is also important as the results will be very sensitive to the aggressiveness. In fact this could be critical to obtaining meaningful results. Stated another way, this aggressiveness rating would describe the care-free handling envelope.

The DRA uses a low, moderate, and high aggressiveness scale defined in the axis of interest by what is intuitively required to achieve low and high gain maneuvering. The moderate level is then defined as the medium value. Improved scaling can be achieved by building a sufficient database. The inherent problem with this approach is the dependency on current technology for the achieved performance. Much more research is required on aggressiveness ratings.

2.2.5.2 Specific Operational Metrics

Operational metrics are a class of metrics that are specific to particular mission tasks, not necessarily an air vehicle type, that reflect realistic aircraft maneuvers. The operational metric is the mission task element (MTE). Defining MTEs provides a means of breaking down typical mission profiles into manageable components that are suitable to both designers and evaluators with the overall aim of being clearly identifiable to the operator.

The mission task element (MTE) was proposed in ADS-33C as a means for standardizing task evaluations. The MTE is useful for flying qualities evaluations and similarly agility evaluations. The usefulness for agility evaluations is perhaps more important given the mission relation of agility. The MTE is the primary operational agility tool for assessing mission suitability. MTE can be applicable to many aircraft missions or unique to one mission therefore no definitive listing can be provided in this study. The MTE list must be produced early in an aircraft's development defined by the customer in the prime vehicle specification. Since the concept is gaining larger use, a more comprehensive listing may be available in the future. At this time, it is certainly the case for helicopter maneuvering and agility studies with the MTEs listed in ADS-33C.

Perhaps one weakness of this approach is that if any particular MTE is considered, the control amplitude or rate used to effect the maneuver will ultimately determine the time to complete the MTE. The MTE may be performed using very different pilot techniques resulting in different answers. This approach is not desirable for repeatability but the results are extremely important for assessing the "real" combat effectiveness of the aircraft. Therefore, it is apparent that some method is required to weight the results of performing a maneuver to the best achievable time.

The best achievable time can be determined in two ways: theoretical prediction or experimentation. Theoretical prediction has been attempted in a limited fashion using what has been referred to as the Agility-Factor or A-Factor. (24) This metric is the ratio of performance used to that available or the theoretically perfect task time to the actual task time. The perfect task time is defined as that achieved when maximum (sustained) acceleration is applied instantaneously. This concept will be discussed in detail in 2.3.1. Experimentation to determine the fastest possible approach could be based on the aggressiveness rating system proposed previously. With a clearly defined mission task, depending on the aggressiveness in application of control inputs, the time to perform the task could vary. Thus, for the "real situation" the time required could be measured. The metrics may be presented as illustrated in Figure 2.2.2. From these approaches, the bounds which on agility may be identified. This should be a major area for investigation to determine the bounds on agility.

The specific operational metrics are perhaps the broadest of the agility metric classes in that so many missions are conceivable. Missions for future aircraft that may be required to be agile include: fighters, attack helicopters, trainers, or even transports. When breaking down these missions into possible profiles and then further into MTEs, some commonality will exist. A large amount of research is required to identify suitable MTE libraries.

Standardization of this effort may pay-off for multi-nation programs. The most active research into potential agility metrics for specific missions has been for the fighter and attack helicopter missions. Consideration should be given to other missions that may benefit from quicker response times.

2.2.5.3 Fighter Metrics

The largest available set of operational metrics associated with a mission are the fighter metrics. With the reduced engagement times associated with modern air-to-air combat, the agile fighter aircraft has become a solution. Butts and Lawless interviewed a large number of fighter pilots and presented in reference 16 four elements of air combat maneuvering which were not adequately addressed by existing measures of merit. These elements were:(16)

1) the ability to change the aircraft's nose position (attitude) relative to the adversary,
2) the ability to change the aircraft's flight path relative to the adversary,
3) the quickness of the changes, and
4) the preciseness of these changes.

These characteristics perhaps best summarized the purposes of the fighter metrics proposed by the community. These metrics are listed in Figure 2.2.8.

Tamrat's Point and Shoot Combat Analysis. Tamrat discussed an approach to analyzing the capability of an aircraft to point its weapons, launch, and destroy an adversary before that adversary could launch a weapon (8). To characterize this capability, Tamrat suggested the pointing margin metric which is shown in Figure 2.2.8. In this case the angles should be measured in an inertial frame to define a relation with respect to an adversary aircraft. The pointing margin was defined as the angle between the nose of the adversary aircraft and the line of sight joining the two aircraft. If the adversary is able to bring the PM to zero and launch prior to the friendly weapon impact, a mutual kill would be possible. Therefore it would be desirable to have a fighter which could nose point quickly, launch quickly, and have a weapon with a short time of flight. The PM data are affected by wing-loading, maximum limit load factor, wing aspect ratio, thrust effects, drag effects, and pitch angle capabilities of an aircraft. Tamrat provides some supporting data for these effects in ref 8.

Tamrat's Relative Energy State. Tamrat suggested the relative energy state (RES) metric to supplement the pointing margin metric because he states that aerial combat is not a first-shot-only phenomenon. The relative energy state then can be expressed as the ratio of the aircraft's airspeed to its corner velocity at the current conditions (altitude, configuration, power setting). This metric being the square of the relative energy at constant altitude and would be calculated after the aircraft made two 90 degree turns before slowing below its corner airspeed. The data was presented versus heading change as shown in Figure 2.2.8 to show the effect of wing loading on the RES. To analyze the effect of airspeed, Tamrat concluded that first-shot capability could be traded off against maneuvering potential energy. Tamrat provided some parametric data in ref 8.

Tamrat's Combat Cycle Time. Maneuvering combat to engage multiple targets involves a cycle of state changes. These changes were characterized by Tamrat (ref 8) as shown in Figure 2.2.8. The state transitions were:

1) pitch up to load factor limit,
2) turn using the load factor of lift limit,
3) unload to low Nz level, and
4) acceleration back to the desired airspeed.

Tamrat proposed the combat cycle time (CCT) as the sum of the times required to perform each of these transitions or segments. The starting airspeed, altitude, and point of weapons launch are left up to the investigator to specify and obviously will impact the time required for each segment. Tamrat suggested that minimum CCT can be achieved by higher wing loadings during small heading changes, whereas, low wing loaded aircraft are better suited for large heading changes (8). This concept is consistent with Skow's time-line approach in paper 10.

<u>Tamrat's Rolling Agility Metric</u>. The flight path roll capability of an aircraft can be characterized by measurement of the rearward separation distance (RSD) as discussed in paper 8. This metric can be used to show the impact of flight path roll performance or elevated angle of attack. Tamrat provides some parametric data in reference 8.

<u>Dynamic Speed Turns</u>. General Dynamics proposed a means of characterizing the energy bleed rates during maneuvering flight. These plots were referred to as Dynamic Speed Turn (DST) plots and are derived from the "dog-house" plot. The preparation of the plots are illustrated in Figure 2.2.9. These plots provide: acceleration/deceleration potential at any airspeed or load factor; airspeed gained/lost as well as average turn rate over the time required to perform a maneuver.

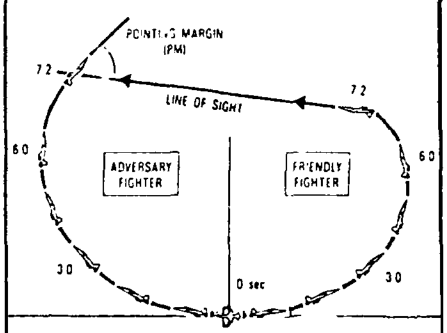
<u>Standard Evaluation Maneuver Set for Agility</u>. The WRDC conducted a large effort to define a complete set of agility tasks with which to evaluate a fighter aircraft. Cord described this effort in reference 15 in its early stages. The task set was referred to as the Standard Evaluation Maneuver Set or STEMS for agility. The concept was based on the existing HQDT approach to evaluating high precision handling qualities during air-to-air tracking. Cord noted that this could be extended to the entire aircraft system for the entire dynamic engagement. Cord also noted that the maneuver set would be constructed so as to be compatible with other metrics. Cord's hypothesis was the HQDT concept can be extended to define simple tasks which capture the essence of agility and flying qualities in an extended flight envelope over a varied range of environments" (15). The challenge of this approach was to produce an approach which could provide meaningful information to both designers and operators.

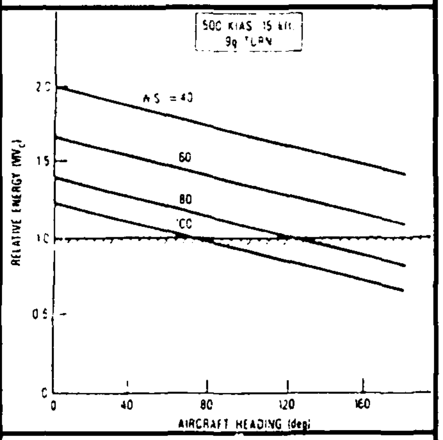
The STEMS for agility proposed when paper 15 was presented is listed in Table 2.2.2. At this point it must be emphasized that this set was incomplete at the time that this paper was presented and a great deal of effort is underway to fully define all the maneuvers. This information is not currently widely available. The fighter MTEs are listed along with: example evaluation tasks, measures of merit, pilot information, and design parameters. The procedure proposed to implement the set in an evaluation was as follows. For each MTE, all possible maneuvers (control strategies) which could be performed by the pilot within the definition of the MTE would first be identified. Once this has been done each maneuver must be dissected to identify specific performance requirements associated with the degree of aggressiveness with which to perform them. Usually, multiple measures of merit are required because the maneuvers are to be executed in more than one axis. One issue that is receiving a great deal of attention now is the pilot information (cueing,flight information etc) necessary to execute the maneuver. For repeatable evaluations this is a very important requirement. Each maneuver must be broken down using this approach in order to get any meaningful data.

### 2.2.5.4 Trainer Agility

Aermacchi has investigated the requirements for advanced fighter training and suggested in ref 12, that to exploit the capabilities of an agile fighter, the trainer must possess similar capabilities to be effective in that mission. The Aermacchi approach was based on the maneuverability and controllability up to some predefined angle of attack. In addition, the task oriented metrics associated with the training mission should be used to ensure that the time required to perform these tasks was minimized and the final condition was met and held for a specified time period. This approach was consistent with the MTE technique discussed thus far.

Figure 2.? 8 Fighter Operational Metrics.

| Symbol | Title | Variables | Simplified Plot |
| --- | --- | --- | --- |
| PM | Pointing Margin | Airspeed<br>Altitude<br>W/s<br>Nz max<br>Aspect Ratio<br>Power Setting<br>Configuration |   |
| **Units** | **Source(s)** | | |
| deg | Tamrat | | |
| **Attribute(s)** | | | |
| A,B1,B3,C,D | | | |

| Symbol | Title | Variables | Simplified Plot |
| --- | --- | --- | --- |
| RES | Relative Energy State | Altitude<br>Configuration<br>Power Setting |   |
| **Units** | **Source(s)** | | |
| N.D. | Tamrat | | |
| **Attribute(s)** | | | |
| A,B1,B3,C,D | | | |

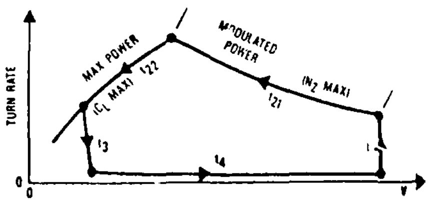
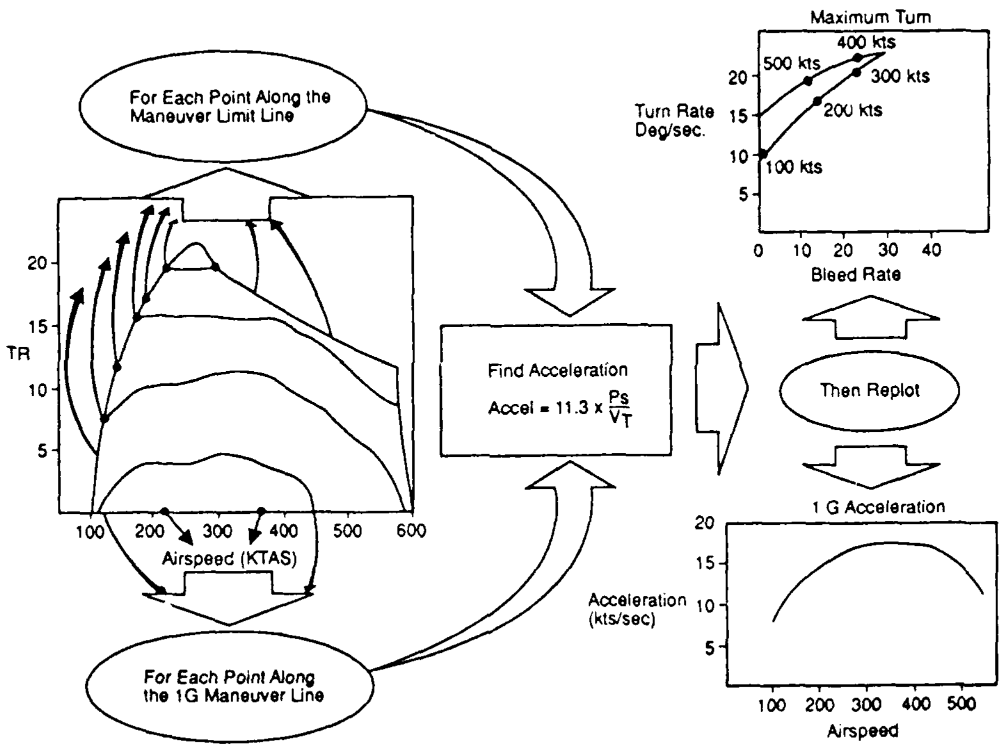
| Symbol | Title | Variables | Simplified Plot |
| --- | --- | --- | --- |
| CCT | Combat Cycle Time | Airspeed<br>Altitude<br>W/s<br>Nz max<br>Aspect Ratio<br>Power Setting<br>Configuration |   |
| **Units** | **Source(s)** | | |
| sec | Tamrat | | |
| **Attribute(s)** | | | |
| A,B1,B3,C,D | | | |

Figure 2.2.9 Dynamic Speed Turn. (2)



| Maneuver Number and Name | Env. | | Axis | | | Data | | Precision | | | | Type | | | Design Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Conventional | High AOA | Longitudinal | Lateral-Directional | Axial | Quantitative | Qualitative | No Capture | Gross Capture | Moderate | Tight Control | Individual Maneuver | Maneuver Sequence | Freestyle Maneuver | Short Period Freq. | Short Period Damping | Maximum AOA | Lon. Command Type | CG Location | Maximum Roll Rate | Roll Time Constant | Engine Time Constant | Vectoring Rate Limits |
| 1. Tracking During High AOA Sweep | | X | X | X | | | X | | | | X | X | | | X | X | | | | X | X | | |
| 2. High AOA Tracking | | X | X | X | | | X | | | | X | X | | | X | X | | | | X | X | | |
| 3. High AOA Lateral Gross Acquisition | | X | | X | | X | X | | | X | | X | X | | | | | | | X | X | | X |
| 4. Dual Attack | X | X | X | X | | | X | | | X | X | | X | X | | | X | | | | | | X |
| 5. Rolling Defense | | X | X | | | X | | X | | | | X | | | | | | | X | X | | | |
| 6. Maximum Pitch Pull | X | X | X | | | X | | X | | | | X | | | X | X | X | | | | | | |
| 7. Nose-Up Pitch Angle Capture | X | X | X | | | X | X | | | X | | X | X | | X | X | | | | | | | |
| 8. Crossing Target Acq. and Tracking | X | X | X | X | | | X | | | X | X | | X | X | X | X | | | | X | X | | |
| 9. Pitch Rate Reserve | | X | X | | | X | | X | | | | X | | | X | X | X | | | | | | |
| 10. High AOA Longitudinal Gross Acq. | | X | X | | | X | X | | | X | | X | X | | X | X | | | | | | | X |
| 11. Sharkenhausen | X | X | X | X | | X | X | | | X | X | | | X | | | X | | | | | | |
| 12. High AOA Roll Reversal | | X | | X | | X | | X | | | | X | X | | | | | | | X | X | | |
| 13. High AOA Roll and Capture | | X | | X | | X | X | | | X | | X | X | | | | | | | X | X | | |
| 14. Minimum Speed Full Stick Loop | X | X | X | | X | | X | X | | | | | X | | | | | | | | | | |
| 15. Minimum Time 180° Heading Change | X | X | X | X | X | | X | | X | | | | | X | | | | | | | | | |
| 16. 1-g Stabilized Pushover | | X | X | | | X | | X | | | | X | | | | | | | | | | | |
| 17. J-Turn | | X | X | X | | | X | | X | | | | X | | X | | | X | | X | | | |
| 18. Tanker Boom Tracking | X | | X | X | X | | X | | | X | X | X | | | X | X | | | | X | | | |
| 19. Tracking in Power Approach | X | | X | X | X | | X | | | X | X | X | X | | X | X | | | | X | | | |
| 20. Offset Approach to Landing | X | | X | X | X | | X | | | X | X | X | X | | X | X | | | | X | | X | |

Table 2.2.2 Standard Evaluation Maneuver Set for Agility.(30)

2.2.5.5 Helicopter Agility

DRA Experience. The Defense Research Agency Bedford investigated how mission oriented tasks could assist in assessing a helicopter's capability to perform aggressively in the nap-of-the-earth environment. DRA concluded that two distinct types or tasks are useful: discrete maneuver element, and continuous tasks (9). The first exercises the aircraft's ability to make quick and precise state changes, whereas, the second demonstrates the pilot control strategy for precise state control.

The discrete maneuver tasks or Mission Task Elements were selected to represent realistic maneuvers. These MTE are illustrated in Figure 2.2.10. These task segments involve multiple pilot inputs using all the aircraft controls. The time to perform the tasks and the precision with which they could be flown were the prime measures of agility.

The continuous task developed by DRA was based on circular flight path.(9) This task was oriented more towards the experimental effort of driving the pilots into high gain and bandwidth conditions looking for deficiencies. In this regard , the task was viewed as a worst case environment.

Sikorsky Experience. Sikorsky conducted a maneuverability/agility (M/A) study of current generation helicopters which was reported in reference 18. The purpose of the study was to determine the sensitivity of various helicopter design attributes on M/A. The obvious benefit of this effort was the definition of guidelines to design in more or less M/A depending on the intended mission profile. This concept was implemented in the Comanche design process. For the study, maneuverability and agility were defined as:

> maneuverability - the ability to change the aircraft's flight path by application of forces from the main rotor, tail rotor, and other control devices, and
>
> agility - how quickly the aircraft flight path can be changed.

Selected helicopters were modelled using a simulator then nine maneuvers were flown for comparison to correlate the various design attributes. These maneuvers will be described here whereas the results of the comparison are left to the reader of reference 18.

The maneuvers were selected on their operational significance to existing combat helicopter tactics. The eight maneuvers and there tactical purpose as defined: (18)

1) Hover bob-up or bob-down. This maneuver is used in a threat environment to provide masking. The helicopter climbs vertically, hovers momentarily to activate sensors or weapons, then rapidly descends to remask. The helicopter holds the same position over the ground and maintain the same heading.

2) Acceleration from Hover to 80 knots (bucket airspeed). It is important for an aircraft to be able to accelerate rapidly from low NOE speeds to the best maneuvering speed (typically 70-80 knots). The altitude and heading are held constant. Other limits were defined for the power available and the nose down pitch angle.

3) Deceleration from 80 knots (bucket airspeed) to Hover. This maneuver is flown to quickly mask the helicopter from potential threats or to position it for an air-to-air encounter with a crossing threat. The altitude is held constant. The rotor could not be over-sped. Other limits were defined for nose-up pitch angle and rotor power required.

4) 80 knot (bucket airspeed) Steady Climb. The ability to quickly climb to engage or to avoid an engagement is an important attribute of a combat helicopter. This maneuver is performed at the bucket airspeed. The maneuver is normally performed in a trimmed for level flight condition.

5) 80 knot (bucket airspeed) Steady Turn. This maneuver is critical from a sustained turn performance perspective (energy-maneuverability). The maneuver is flown at a constant airspeed and altitude at the

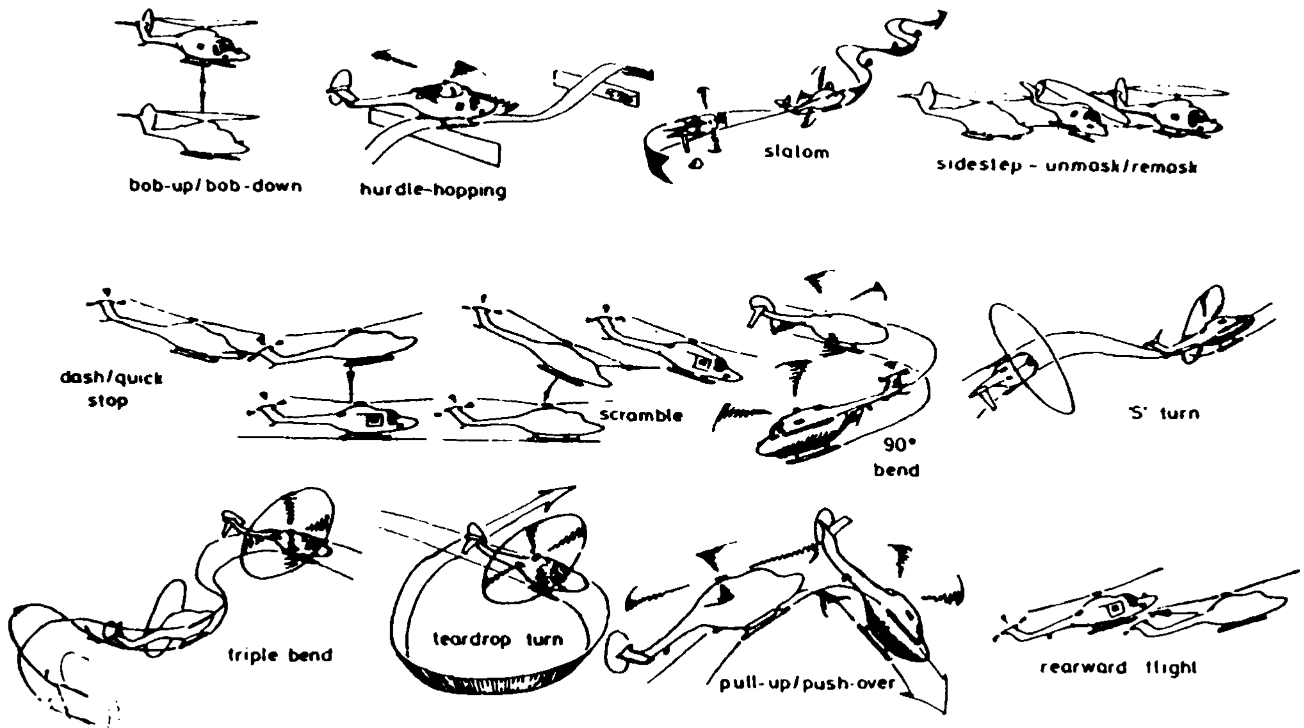



Figure 2.2.10 RAE Helicopter MTEs. (9)

maximum sustainable load factor.

6) 80 knot (bucket airspeed) Decelerating Turn. This maneuver is performed with the intention of turning as quickly as possible without regard for exit speed. The maneuver was limited by the rotor stall incipient stall condition.

7) 130 knot (high speed) Decelerating Turn. Same as 6 only starting at a higher energy state.

8) 140 knot pull-up. A maneuver which is performed if a rapid change in altitude is required (obstacle clearance, threat avoidance). Limited by rotor thrust capability.

9) 180 degree hover turn. This maneuver is important for targeting and attack. The maneuver was performed at constant altitude and turn to 180 degrees from the current heading with no overshoot. The maneuver was limited by yaw rate.

To determine the sensitivity of a helicopter design, the fundamental parameters were correlated to a measure of effectiveness (MOE) which was essentially an agility design parameter for each maneuver. This effort is summarized in Table 2.2.3. The authors noted that broad guidelines would be difficult to specify for the entire airspeed range of operation. Therefore, depending on the mission profile, this approach appears to provide to guidance for the values which can effect M/A.

Table 2.2.3 Helicopter Fundamental Design Parameters which Effect M/A. (18)

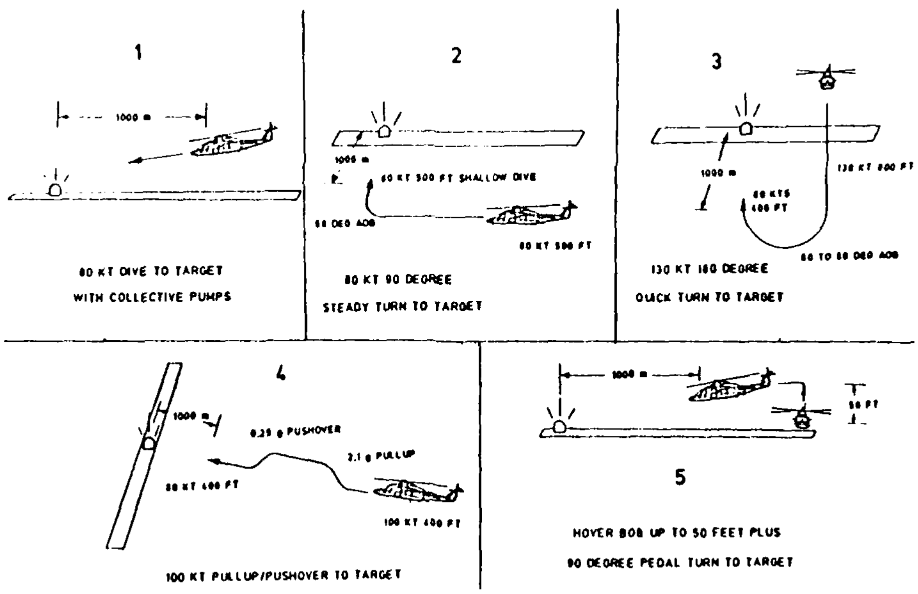
| Maneuver | Fundamental Parameter | MOE |
|---|---|---|
| Hover Bob-up | Hover Maximum Thrust to Gross Weight Ratio | Maximum Rate of Climb |
| Acceleration Hover to 80 knots | Normalized Power Margin | Time to 80 knots |
| Deceleration 80 knots to Hover | Hover Power Required divided by Gross Weight | Time to Hover |
| 80 knots Steady Climb | Normalized Power Margin | Maximum Rate of Climb |
| 80 knots Steady Turn | Power loading divided by Blade loading | Maximum Normal Load Factor |
| 80 knots Decelerating Turn | Nondimensional Thrust Margin | Turn Rate |
| 130 knot Decelerating Turn | Nondimensional Thrust Margin | Turn Rate |
| 140 knot Pullup | Nondimensional Thrust Margin | Maximum Normal Load Factor |
| 180 degree Hover Turn | Tail Rotor Solidity | Time to Turn |

A Sikorsky study was also conducted on the impact on mission effectiveness of helicopter modifications during target acquisition and tracking (11). Acquisition time, target tracking accuracy, and maneuver aggressiveness were the mission effectiveness measures. An instrumented S-76A was used as the test bed for this study. The aircraft was evaluated with the production fuel control system then with an adaptive fuel controller. The aircraft was flown through five mission tasks illustrated in Figure 2.2.11. Pilot qualitative comments, pilot control movements (summed deviation about a running mean), and pilot control power spectrum data were recorded along with the vertical/horizontal errors (in mils) to track the target during each mission task. The results due to the adaptive fuel controller were:

1) a tighter shot pattern
2) reduced pilot workload
3) reduced attitude deviation due to power changes
4) allowed more aggressive maneuvering while reducing targeting workload
5) improved the S-76A H-V avoid area

These results demonstrated that by reducing the pilot workload through automation, more precise aggressive maneuvering could be achieved due to increased pilot workload. By using MTEs and clearly defined measures of effectiveness a reduction in time to perform a task can be demonstrated.

Figure 2.2.11 Helicopter Air-to-Ground Tracking Mission Tasks.(11)



### 2.2.5.6 ASW Helicopters

The ASW Helicopter mission is a potential application for agility although the aircraft are generally not required to dynamically maneuver. The helicopter does not have the same NOE constraints as land tactical helicopters. The mission profile would typically include takeoff from the ship, dash to an operating area, engage an adversary, maneuver defensively, return to ship, and land. For the airborne cases away from the mother ship, the Table 2.2..3 MTE would be sufficient to characterize airframe agility. With a time constraint, landing on the shipdeck and takeoff could also be included.

### 2.2.5.7 Other Missions

Other missions that could benefit from fixed or rotary wing MTE for operational agility could include tactical transport aircraft and V/STOL aircraft. The latter would employ a mixture of both fixed and rotary wing metrics. Further specific study of mission related agility metrics should be conducted to create a library of MTEs that could be grouped by aircraft category as is done in Mil-Std-1797.

## 2.2.6 Application of the Metric Classification

To this point, a metric classification scheme has been suggested and existing airframe metrics described. It is appropriate at this point to apply the scheme to an example. Since traditional agility research has been conducted on fighter aircraft many metrics are readily available. The classic time critical event is a missile engagement sequence. This scenario was used by Skow. (10) For this situation let us assume that the fighter is cruising above corner velocity at 20,000 ft. The fighter pilot has detected an adversary aircraft which must be engaged and if destroyed the fighter must be recovered to the same starting conditions in order to be ready to repeat the sequence. To employ its missile, the aircraft must make some specified nose pointing transition simultaneously using a heading and pitch angle change. With these constraints, metrics can be suggested that focus on time critical events during the engagement. Consider a time-line that includes all the sequential tasks that must be performed by the pilot. The tasks would include: pilot decision; avionics processing; aircraft maneuvering; missile launch; missile fly-out; engagement end-game; and if successful aircraft recovery to cruise conditions. Several of the tasks could be performed in parallel. Since only airframe metrics have been presented thus far, aspects of the operator, avionics, and weapons will be left to future chapters.

The metric hierarchy facilitates a top-down analysis approach to this engagement. This provides an overall view of how quick the task can be accomplished at the same time as identifying the characteristics of the constituent task elements. Relevant airframe metrics are presented in Figure 2.2.12 according to the time regime of interest. A designer may look to reduce the engagement time so as to be more operationally effective by being able to engage more aircraft.

The maneuver sequence provides a basis on which to break the task into MTEs. These include: roll-in; horizontal turn; unload after launch; and acceleration to recover. At the MTE level, the designer can identify for which MTE is/are the reason for the excessive time delays. Other operational metrics specific to the fighter such as the CCT or PM parameter will provide guidance for comparison with threat knowledge or the response and launch times. The horizontal turn which for a current generation fighter typically bends its flight path, could be improved with technologies that permit rapid nose pointing, such as thrust vectoring.

The experimental metrics provide the tools to investigate those airframe MTEs that are too long. The selection of what experimental metrics are appropriate would depend on the motion occurring. For example, the roll-in could be characterized by the torsional metrics such as the LA, TA, or Roll AQP. The rapid nose-pointing with thrust vectoring will likely result in a large drag increase so power rate metric will assist in analyzing that transition event.

Throughout the sequence transient metrics identify when the peak state change events occur. At this point, the components of the agility vector as well as more traditional metrics provide direct relation of the motion to key design elements, such as CLmax and T/W. This procedure occurs at the lowest level of detail. At this level the instantaneous response of the aircraft can be analyzed. Another technique that has been proposed by researchers at the AFFTC is onset and capture transient analysis. This technique will be described further in Chapter 2.5.

To date, data are only available for some of these characteristics. This deficiency should be rectified in order to gain a deeper appreciation of the tactical meaning of agility concepts. In addition, other important time critical scenarios should be investigated.

Figure 2.2.12 Hypothetical WVR Missile Engagement Time-Line.

Task Definition: Missile Engagement for target at $\Delta\theta$ $\Delta\psi$ While Cruising at 450 knots at 20,000 ft PA in the Interceptor Configuration.

**Global Operational Metrics:**

$t_{ME}$ = time to transition from cruise, launch missile, and return to cruise airspeed.

Other metrics: energy-agility, tracking accuracy, aggressiveness rating

$CCT = t_{ROLL} + t_{TURN} + t_{UNLOAD} + t_{ACCEL}$

DT Parameter

**Specific Operational Metrics:**

| | CRUISE | ROLL IN | HORIZONTAL TURN | MISSILE LAUNCH | UNLOAD | ACCELERATE | CRUISE |
|---|---|---|---|---|---|---|---|
| MISSION TASK ELEMENTS | | $t_{ROLL}$ | $t_{TURN}$ | | $t_{UNLOAD}$ | $t_{ACCEL}$ | |

**Experimental Metrics:**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| DISCRETE CHARACTERISTICS | | LA<br>TA<br>$P_{pk}$<br>$t_{\Delta\theta}$<br>$Q_{pk}$<br>PAP<br>PR | PR<br>$t_{\Delta\psi}$<br>$Nz_{pk}$ | | PR<br>$t_{\Delta Nz}$<br>$\frac{dNz}{dt}_{pk}$ | $a_{x\,pk}$<br>$t_{pk\,ax}$<br>PR | |

**Transient Metrics:**


| | | | |
|---|---|---|---|
| $\theta$ | pitch angle | PR | power rate |
| $\psi$ | heading angle | PAP | pitch attitude quickness parameter |
| a | acceleration (x axial) | Nz | Normal loa fac!or |
| $A_A$ | agility vector axial component | t | time to perfm a mission task |
| $A_C$ | agility vector curvature component | pk | peak |
| $A_T$ | agility vector torsional component | | |
| CCT | combat cycle time | | |
| LA | lateral agility | | |
| P | roll rate | | |
| Q | pitch rate | | |

### 2.2.7 Conclusions and Recommendations

This section developed a classification scheme for use in grouping the numerous metrics proposed in the literature. This scheme will be beneficial for identifying critical gaps in the available knowledge but perhaps more importantly establish agility as a design objective and permit clearer specifications.

Based on the study of current airframe agility metric research it is apparent that the following critical gaps still exist:

1) there still does not seem to be a consensus on the tactical meaning and usefulness of airframe agility metrics (all the results are still relatively indirect confirmation that agility improves effectiveness with quick engagement times), ie B3 Attribute.

2) fixed wing metrics are more abundant than rotary wing metrics.

To further develop airframe agility metrics it is recommended that:

1) the difference between pure nose pointing with respect to the velocity vector, pure flight path bending, or a combination of the two be clarified.

2) more data for quickness parameters for fixed wing aircraft (these metrics will likely map out the bounds on agility) be gathered

3) an aggressiveness rating system be developed.

4) a library of MTEs (this would show common MTEs and mission unique MTEs) be established.

5) more flight test data for transient, experimental, and operational metrics be gathered.

6) a rotary wing research master plan such as was suggested by Dorn for fighter aircraft be developed.

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## 2.3 The Influence of Flying Qualities on Airframe Agility

### Abstract

Flying Qualities standards are formally set to ensure safe flight and therefore to reflect minimum, rather than optimum, requirements. Agility is a flying quality but relates to operations at high, if not maximum, performance. While the quality metrics and test procedures for flying, as covered for example in Mil Std 1797 or ADS33, may provide an adequate structure to encompass agility, they do not currently address flight at high performance. A current concern in both fixed and rotary-wing communities is the absence of substantiated agility criteria and possible conflicts between flying qualities and high performance, eg more may not always be better. This Chapter addresses these concerns and some novel perspectives on the subject are presented including the agility factor, that quantifies performance margins in flying qualities terms. The attitude quickness, from the latest rotary-wing handling requirements provides an ideal agility measure and links handling with agility; a new parameter, based on manoeuvre acceleration, is introduced as a potential candidate for defining upper limits to flying qualities. These concepts are introduced within a framework aimed at unifying flying qualities and performance requirements. Finally a probabilistic analysis of pilot handling qualities ratings is presented that suggests a powerful relationship between inherent airframe flying qualities and operational agility.

### 2.3.1 Introduction

In current military requirements, good flying qualities are conferred to ensure that safe flight is guaranteed throughout the Operational Flight Envelope (OFE). Goodness, or quality, in flying can be measured on a scale spanning three Levels, as defined by Cooper-Harper (Ref 1). Aircraft are normally required to be Level 1 throughout the OFE (Ref 2, 3); Level 2 is acceptable in failed and emergency situations but Level 3 is considered unacceptable. The achievement of Level 1 quality signifies that a minimum required standard has been met or exceeded in design and can be expected to be achieved regularly in operational use, measured in terms of task performance and pilot workload. Compliance flight testing involves clinical measurements of flying qualities parameters for which good values are known from experience; it also involves the performance of pilot-in-the-loop mission task elements (MTE) along with the acquisition of subjective comments and pilot ratings. The emphasis on minimum requirements is important and is made to ensure that manufacturers are not unduly constrained when conducting their design trade studies.

Two issues arise out of this quality scale and assessment. First, the minimum requirements reflect and exercise only moderate levels of the dynamic OFE, rather than high or extreme levels. Second, the assessments are usually made in 'clean' conditions, uncluttered by secondary tasks, degraded visual cues or the stress of real combat. Beyond the minimum quality levels there remains the question of the value of good flying qualities to the overall mission effectiveness. For example, how much more effective is an aircraft that has, say, double the minimum required (Level 1) roll control power? More generally, how much more mission effective is a Level 1 than a Level 2 aircraft when, for example, the pilot is stressed? A third question asks whether there are any upper limits to the flying qualities parameters, making quality boundaries closed contours. The answers to these questions cannot generally be found in flying qualities criteria like ADS33 (Ref 2) or Mil Std 1797 (Ref 3). At higher performance levels, very little data are available on flying qualities and, consequently, there are very few defined upper limits on handling parameters. Regular and safe, or carefree, use of high levels of transient performance has come to be synonymous with agility. The relationship between flying qualities and agility is important because it potentially quantifies the value of flying qualities to operational effectiveness.

The issues that this Chapter addresses then, concern the flying qualities that are important for agility, in both an enabling and limiting context, and how far existing flying qualities requirements go, or can be extended, to embrace agility itself. The answers are developed within a framework of deterministic flying qualities criteria coupled with the probabilistic analysis of success and failure.

The definition of flying qualities by Cooper & Harper (Ref 1) provides a convenient starting point,

***'those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role'.***

The pilot subjective rating scale and associated flying qualities Levels as introduced by Cooper & Harper (Fig 2.3.1) will be used in this paper in the familiar context of quality discernment and will be developed to make the link with agility and mission effectiveness.

Flying 'Quality' can be further interpreted as the synergy between the **internal attributes** of the air vehicle and the **external environment** in which it operates (Fig 2.3.2). The internals consist typically of the air vehicle (airframe, powerplant and flight control system) response characteristics to pilot inputs (handling qualities) and

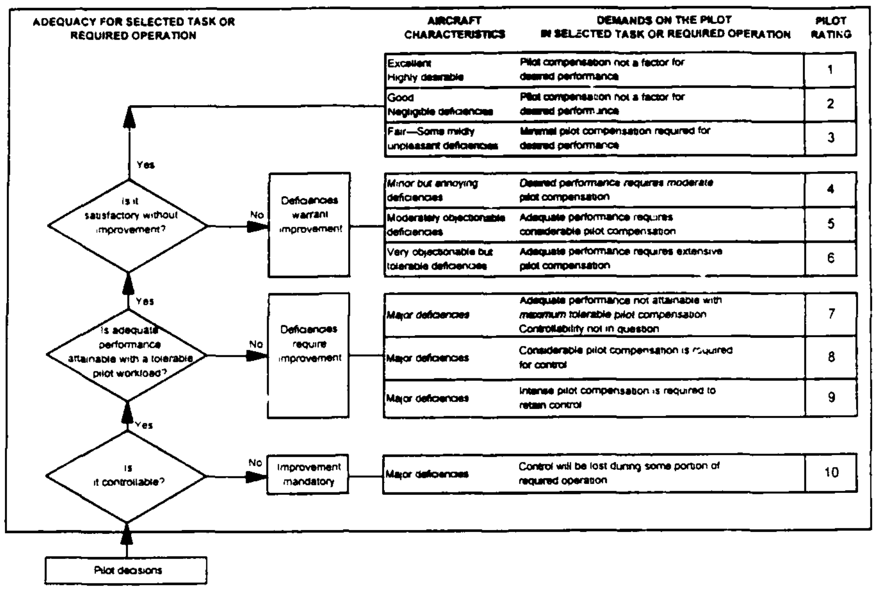



**Fig 1 The Cooper Harper Handling Qualities Rating Scale**

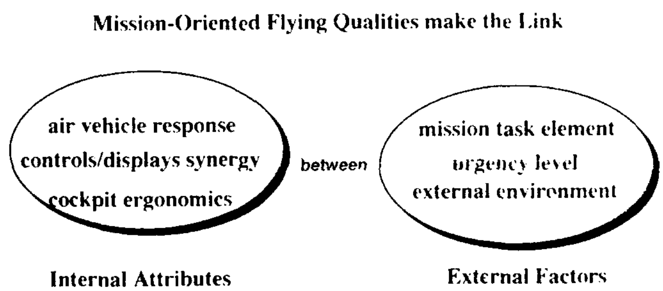



**Fig 2 The Synergy of Flying Qualities**

disturbances (ride qualities) and the key elements at the pilot/vehicle interface eg cockpit controls and displays. The key factors in the external environment which influence the flying qualities requirements are:

i) the mission, including individual mission task elements (MTE) and the required levels of task urgency and divided attention dictated by the circumstances governing individual situations, eg threat level.

ii) the external natural environment, including the usable cue environment (UCE - Ref 2) and level of atmospheric disturbance.

Flying qualities, as seen by the pilot who is ultimately the judge of quality, therefore change as the external world changes; for example, with weather conditions and flight path constraints and other task demands. Mission oriented flying qualities requirements, like those for fixed-wing aircraft, MIL STD 1797, but more particularly, helicopters in

ADS33C, try to set quality standards by addressing the synergy of these internal attributes and external factors. In a hierarchical manner, ADS33C defines the response types required to achieve Level 1 or 2 handling qualities for a wide variety of different mission task elements, in different usable cue environments for normal and failed states, with full and divided pilot attention. At a deeper level, the response characteristics are broken down in terms of amplitude and frequency range, from the small amplitude, higher frequency requirements set by criteria like equivalent low order system response or bandwidth, to the large amplitude manoeuvre requirements set by control power. Mil Std 1797 takes a somewhat different perspective, with flight phases and aircraft categories, but the basic message is the same - how to establish flying quality. With these developments now mature, one would expect that any 'special' flying characteristics, like agility, could be embraced by the flying qualities requirements, or at least that the flying qualities criteria should be an appropriate format and starting point for quantifying agility. A key question then arises as to whether there need to be upper boundaries on handling parameters or whether more is always better? Furthermore, it may well be that the handling parameters and associated quality boundaries set for minimum safety standards are inappropriate for high performance levels and that new formats are required. These are primary concerns of this Chapter.

The Chapter considers both fixed and rotary-wing aircraft in a unified approach. While speed and manoeuvre envelopes and associated limits for aeroplanes and helicopters are quite different, often paradoxically so, they share the essence of agility and operational effectiveness. Interestingly, agility requirements for the two vehicle types have traditionally stemmed from two quite different theatres; close combat of air-superiority fighters in the open skies contrasting with stealth of anti-armour helicopters in the nap-of-the-earth. While both still feature large in the two worlds, it is now recognised that there is a broad overlap in agility requirements and there is relevance to a wider range of roles including aircraft recovering to ships, transport refuelling, support helicopters delivering loads into restricted areas and, more recently, helicopter air-to-air combat.

AGARD Working Group 19 has considered operational agility in the broader context of the total weapon system, encompassing sensors, mission systems, pilot, airframe/engine, flight control system and weapon; the concept is that the total system can only be as agile as the slowest element and that all elements need to work concurrently to be effective. This Chapter focuses on the vehicle and the pilot centred agility requirements of the airframe, engine and flight control system elements. The nature of operational agility, is discussed, with an outline of some of the Working Group 19 background and motivation setting the scene for the later Sections which address the relationship between flying qualities and agility. Three key innovations of this Chapter are contained here; first, the agility factor is introduced and related to quantitative handling criteria. Second, the attitude quickness parameter (Ref 2) is interpreted as an agility parameter and extended to the acceleration response. Finally, the subjective quality scale (Cooper Harper) for pilot-perceived handling qualities is interpreted in a probabilistic fashion to indicate the likelihood of mission success or failure with a given level of flying qualities. Essentially, recognition is given to the fact that aircraft that are, say Level 1 on 'paper', will experience Level 2 and 3 situations in their operational life, eg through poor UCE and associated weather conditions, failed systems or pilot fatigue. This novel interpretation of the handling quality ratings suggests a new approach for including flying qualities attributes in combat models, which are discussed.

### 2.3.2 The Nature of Operational Agility

Operational agility is a key attribute for weapon system effectiveness. Within the broader context of the total weapon system, the Mission Task naturally extends to include the actions of the different co-operating (and non-co-operating) sub-systems, each having its own associated time delay (Ref 4). We can imagine, for example, the sequence of actions for an air-to-air engagement - threat detection, engagement, combat and disengagement; the pilot initiates the action and stays in command throughout, but a key to operational agility is to automate the integration of the subsystems - the sensors, mission systems, airframe/engine/control systems and weapon, to maximise the concurrency in the process. Concurrency is one of the keys to Operational Agility. Another key relates to minimising the time delays of the subsystems to reach full operational capability and hence effectiveness in the MTE. Extensions to the MTE concept are required that encompass the functions and operations of the subsystems, providing an approach to assessing system operational agility. WG19 has addressed these issues in other Chapters to this report. Minimising time delays is crucial for the airframe, but flying qualities can suffer if the accelerations are too high or time constants too short, leading to jerky motion.

Later in this paper we examine how well existing flying qualities requirements address agility; to set the scene for this, we first consider the generalised definition of agility adopted by Working Group 19;

***"the ability to adapt and respond rapidly and precisely with safety and with poise, to maximise mission effectiveness"***

Agility requirements for both fixed and rotary-wing combat aircraft fall into four key mission phases;

a) stealthy flying, in particular terrain-masked, to avoid detection,

b) threat avoidance once detected,

c) the primary mission engagement (eg threat engagement) and,

d) recovery and launch from confined, or otherwise demanding, areas.

The key attributes of airframe agility, as contained in the above definition are,

i) rapid - emphasising speed of response, including both transient and steady state phases in the manoeuvre change; the pilot is concerned to complete the manoeuvre change in the **shortest possible time;** what is possible will be bounded by a number of different aspects.

ii) precise - accuracy is the driver here, with the motivation that the greater task precision eg pointing, flight path achievable, the greater the chance of a successful outcome.

*(The combination of speed and precision emphasises the special nature of agility: one would normally conduct a process slowly to achieve precision, but agility requires both)*

iii) safety - this reflects the need to reduce piloting workload, making the flying easier and freeing the pilot from unnecessary concerns relating to safety of flight, eg respecting flight envelope limits.

iv) poise - this relates to the ability of the pilot to establish new steady state conditions quickly and to be free to attend to the next task; it relates to precision in the last moments of the manoeuvre change but is also a key driver for ride qualities that enhance steadiness in the presence of disturbances.

*(Poise can be thought of as an efficiency factor, or measure of the unused potential energy, much like the agility factor itself).*

v) adapt - the special emphasis here relates to the requirements on the pilot and aircraft systems to be continuously updating awareness of the operational situation; the possibility of rapid changes in the external factors discussed above (eg threats, UCE, wind shear/vortex wakes) or the internals, through failed or damaged systems, make it important that agility is considered, not just in relation to set-piece manoeuvres and classical engagements, but also for initial conditions of low energy and/or high vulnerability or uncertainty.

Flying qualities requirements address some of the agility attributes implicitly, through the use of the handling qualities ratings (HQR), that relate the pilot workload to task performance achieved, and explicitly through criteria on response performance, eg control power, bandwidth, stability etc. The relationship is more firmly established with the agility metric classification introduced by Reif in Chapter 2.2 of this report, and reproduced below.

**Transient** - defined as a continuously varying property of the response

**Experimental** - defined as a compound property derived form an elemental manoeuvre

**Operational** - defined as a compound property derived from a complete mission-task-element

A transient metric would reflect the instantaneous values of the time and spatial variations of the aircraft's motion, eg roll rate, acceleration (agility vector). Experimental metrics are computed from the kinematics of a small manoeuvre slice, eg attitude quickness, power onset/loss rate, torsional metrics. The operational metrics reflect the agility of the aircraft in well defined mission task elements, eg time to complete air-to-air acquisition and tracking, helicopter re-positioning sidestep tasks. In the following section, where possible, this classification structure will be mapped onto flying qualities metrics.

### 2.3.3 Flying Qualities - the Relationship with Agility

#### *Fixed-Wing Perspectives*

One of the fundamentals that Working Group 19 promoted is that flying qualities and airframe agility are outgrowths from the same attribute branch, but recent studies have identified a potential conflict. The original concern sprang

from the notion that flying qualities specifications, as guardians of transient response, should embrace agility, since it too resides by definition in the transient domain. Initial thoughts on this theme appeared in Refs 5 and 6. Reference 5 indicated the interactions between agility, operational capability and flying qualities and listed some of the flying qualities requirements that, because of their treatment of the transient response, clearly crossed into the realm of agility. At that time, it was hypothesized that simply increasing the available agility, in terms of accelerations, rates etc, would lead to diminishing operational returns, since an over-responsive vehicle would not be controllable. That point was considered worth making because some combat analyses were being performed using computer tools that approximated the transient response only in a gross fashion. These models resulted in aircraft which had unquestionably high performance but did not account for the interaction of the vehicle with the pilot. Also, due to the approximations made in the interests of computational tractability, the models did not obey the laws of motion in their transient responses. In Ref 6, the Control Anticipation Parameter (CAP) from the USAF Flying Qualities requirements (Ref 3), was quoted as an example of a criterion defining over-responsiveness, since an upper limit is specified for it. Artificially high pitch agility could, according to CAP, correspond to excessive pitch acceleration relative to the normal load factor capability of the aircraft. Performance constraints are also suggested by the tentative upper limits set on pitch bandwidth in Reference 3, although it is suspected that this is a reflection of the adverse acceleration effects and control sensitivity problems associated with high bandwidth/control power combinations. This point will be returned to later.

At about the same time, Riley et al at McAIR began a series of experiments on fighter agility. In Ref 7, they emphasised that the definition of the categories in the Cooper-Harper pilot rating scale precluded the idea of an operationally useful vehicle with a rating worse than Level 2. In Level 3, the operational effectiveness of the vehicle is compromised, so increasing performance would add little as the pilot could not use it safely. In Refs 7, 8 and 9, Riley and Drajeske describe a fixed-base simulation in which the maximum available roll rate and roll mode time constant were independently varied and the pilot's time to bank 90 degrees and stop was measured. Care was taken in the experiment to allow sufficient time for learning and to generate reasonably large numbers (10 to 15) of captures for analysis. The start of the manoeuvre was when the stick deflection began, and the end was defined as when the roll rate was arrested to less than 5 degrees/second, or 5% of the maximum rate used, whichever was greater. Therefore a realistic element of precision was introduced into the protocol. The results from that experiment, in which the aircraft banked from -45 degrees to +45 degrees, are shown in Fig 2.3.3. The lower curved surface summarizes the calculated time responses for a step lateral input and shows the expected steady increase in agility, ie a decrease in the time to bank with increasing roll rate. The upper surface in the plot summarizes the bank - to - bank and stop data obtained in the piloted cases. The references to controllability on that surface are from the pilot ratings and comments that were collected. The time to complete the manoeuvre actually increases for the higher available roll rates because the pilot could not adequately control the manoeuvre. The data therefore show that flying qualities considerations do limit agility. Though the data are from fixed-base simulation, we can speculate that in - flight results might show still more dramatic limitations. In Ref 9 the authors suggest that the effects of motion would in fact change the shape of Figure 3 to look like Fig 2.3.4.

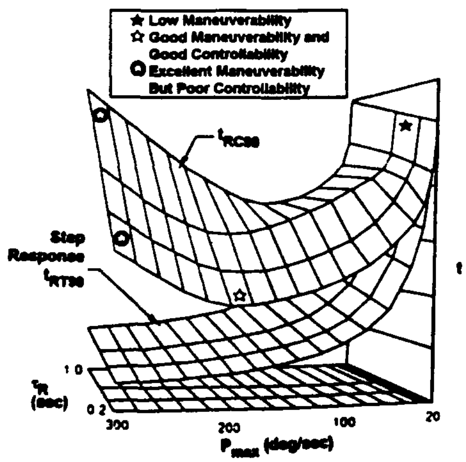



Fig 2.3.3 Agility in a Roll Manoeuvre (Ref 7)

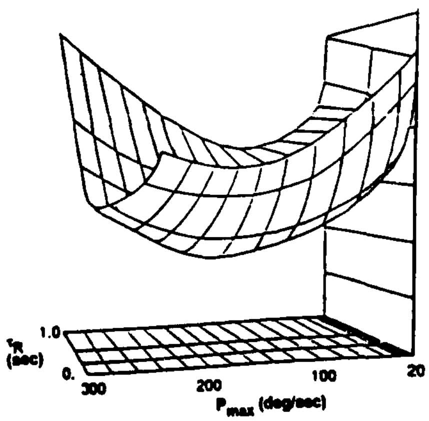



Fig 2.3.4 Effects of Motion on Agility

In Mil Std 1797, upper limits on lateral flying qualities are almost exclusively set by tolerable levels of acceleration at the pilot station, in the form of lateral g per control power; the Level 1 boundary at about 2g for a typical fighter seems extraordinarily high, but Reference 3 does state that "in order to achieve the needed roll performance it may be necessary to accept some uncomfortable lateral accelerations". There is considerable discussion on lateral control sensitivity in Reference 3, but, as with helicopters, the criteria are strongly dependent on controller type and only guidance is given. Clearly there will always be upper limits to sensitivity and it should be an important goal to design the pilot/vehicle interface so that agility is not inhibited by this parameter.

***Rotary-Wing Perspectives & The Agility Factor***

One of the most common causes of dispersion in pilot HQRs stems from poor or imprecise definition of the performance requirements in a mission task element, leading to variations in interpretation and hence perception of achieved task performance and associated workload. In operational situations this translates into the variability and uncertainty of task drivers, commonly expressed in terms of precision, but the temporal demands are equally important. The effects of task time constraints on perceived handling have been well documented (Refs 10, 11, 12), and represent one of the most important external factors that impact pilot workload. Flight results gathered on Puma and Lynx test aircraft at DRA (Refs 12, 13) showed that a critical parameter was the ratio of the task performance achieved to the maximum available from the aircraft; this ratio gives an indirect measure of the spare capacity or performance margin and was consequently named the agility factor. The notion developed that if a pilot could use the full performance safely, while achieving desired task precision requirements, then the aircraft could be described as agile. If not, then no matter how much performance margin was built into the helicopter, it could not be described as agile. The Bedford agility trials were conducted with Lynx and Puma operating at light weights to simulate the higher levels of performance margin expected in future types (eg up to 20-30% hover thrust margin). A convenient method of computing the agility factor was developed as the ratio of ideal task time to actual task time. The task was deemed to commence at the first pilot control input and complete when the aircraft motion decayed to within prescribed limits (eg position within a prescribed cube, rates < 5 deg/s) for re-positioning tasks or the accuracy/time requirements met for tracking or pursuit tasks. The ideal task time is calculated by assuming that the maximum acceleration is achieved instantaneously, in much the same way that some aircraft models work in combat games. So, for example, in a sidestep re-positioning manoeuvre, the ideal task time is derived with the assumption that the maximum ***translational*** acceleration (hence aircraft roll angle) is achieved instantaneously and sustained for half the manoeuvre, when it is reversed and sustained until the velocity is again zero.

The ideal task time is then simply given by

$$T_i = \sqrt{(4S/a_{max})} \qquad 1$$

where S is the sidestep length and $a_{max}$ is the maximum translational acceleration. With a 15% hover thrust margin, the corresponding maximum bank angle is about 30deg, with $a_{max}$ equal to 0.58g. For a 100ft sidestep, $T_i$ then equals 4.6 seconds. Factors that can increase the achieved task time, beyond the ideal, include,

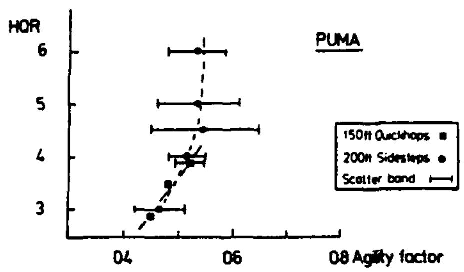
i) delays in achieving the maximum acceleration (eg due to low roll attitude bandwidth/control power)

ii) pilot reluctance to use the max performance (eg no carefree handling capability, fear of hitting ground)

iii) inability to sustain the maximum acceleration due to drag effects and sideways velocity limits

iv) pilot errors of judgement leading to terminal re-positioning problems (eg caused by poor task cues, strong cross coupling)

To establish the kinds of agility factors that could be achieved in flight test, pilots were required to fly the Lynx and Puma with various levels of aggressiveness or manoeuvre 'attack', defined by the maximum attitude angles used and rate of control application. For the low speed, re-positioning Sidestep and Quickhop MTEs, data were gathered at roll and pitch angles of 10, 20 and 30 degs corresponding to low, moderate and high levels of attack respectively. Fig 2.3.5 illustrates the variation of HQRs with agility factor. The higher agility factors achieved with Lynx are principally attributed to the hingeless rotor system and faster engine/governor response. Even so, maximum values of only 0.6 to 0.7 were recorded compared with 0.5 to 0.6 for the Puma. For both aircraft, the highest agility factors were achieved at marginal Level 2/3 handling; in these conditions, the pilot is either working with little or no spare capacity or not able to achieve the flight path precision requirements.



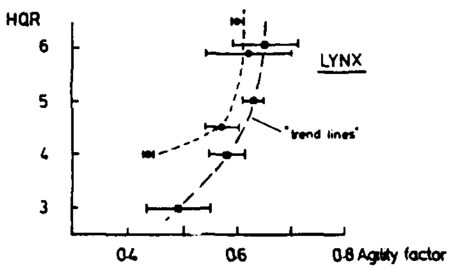




**Fig 2.3.5 Variation of HQR with $A_f$ - Puma    Fig 2.3.5 Variation of HQR with $A_f$ - Lynx**

According to Fig 2.3.5, the situation rapidly deteriorates from Level 1 to Level 3 as the pilot attempts to exploit the full performance, emphasising the 'cliff edge' nature of the effects of handling deficiencies. The Lynx and Puma are typical of current operational types with low authority stability and control augmentation; while they may be adequate for their current roles, flying qualities deficiencies emerge when simulating the higher performance required in future combat helicopters.

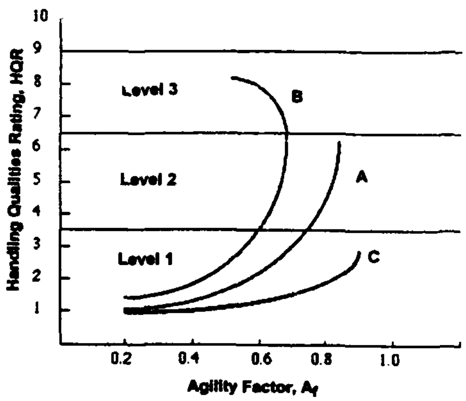



**Fig 2.3.6 Variation of HQR with $A_f$ for Different Notional Configurations**

The different possibilities are illustrated in Fig 2.3.6. All three configurations are assumed to have the same performance margin and hence ideal task time. Configuration A can achieve the task performance requirements at high agility factors but only at the expense of maximum pilot effort (poor level 2 HQR); the aircraft cannot be described as agile. Configuration B cannot achieve the task performance when the pilot increases his attack and Level 3 ratings are returned; in addition, the attempts to improve task performance by increasing manoeuvre attack have led to a decrease in agility factor, hence a waste of performance. This situation can arise when an aircraft is PIO prone, is difficult to re-trim or when control or airframe limits are easily exceeded in the transient response. Configuration B is certainly not agile and the proverb 'more haste, less speed' sums the situation up. With configuration C, the pilot is able to exploit the full performance at low workload; he has spare capacity for situation awareness and being prepared for the unexpected. Configuration C can be described as truly agile. The inclusion of such attributes as safeness and poise within the concept of agility emphasises its nature as a flying quality and suggests a correspondence with the quality Levels. These conceptual findings are significant because the flying qualities boundaries, that separate different quality levels, now become boundaries of available agility. Although good flying qualities are sometimes thought to be merely "nice to have", with this interpretation they can actually

delineate a vehicle's achievable performance. This lends a much greater urgency to defining where those boundaries should be. Put simply, if high performance is dangerous to use, then most pilots will avoid using it.

In agility factor experiments the definition of the level of manoeuvre attack needs to be related to the key manoeuvre parameter, eg aircraft speed, attitude, turn rate or target motion. By increasing attack in an experiment, we are trying to reduce the time constant of the task, or reducing the task bandwidth. It is adequate to define three levels - low, moderate and high, the lower corresponding to normal manoeuvring, the upper to emergency manoeuvres.

There are also potential mis-uses of the agility factor when comparing aircraft. The primary use of the Af is in measuring the characteristics of a particular aircraft performing different MTEs with different performance requirements. However, Af also compares different aircraft flying the same MTE. Clearly, a low performance aircraft will take longer to complete a task than one with high performance, all else being equal. The normalising ideal time will also be greater, and if the agility factors are compared, this will bias in favour of the poor performer. Also, the ratio of time in the steady state to time in the transients may well be higher for the low performer. To ensure that such potential anomalies are not encountered, when comparing aircraft using the agility factor it is important to use the same normalising factor - defined by the ideal time computed from a performance requirement. The agility factor concept, as an operational agility metric, was developed in the surge of rotary-wing handling qualities developments over the last ten years. It is equally applicable to fixed-wing aircraft, although the associated MTE database will need to be developed as a foundation.

Conferring operational agility on future fixed and rotary - wing aircraft, emulating configuration C above in Fig 2.3.6, requires significant improvements in handling, particularly for rotorcraft, but research into criteria at high performance levels and innovations in active control are needed to lead the way. There are two remaining links to be connected to assist in this process. First, between the agility factor and the operational agility or mission effectiveness and second between the agility factor and the flying qualities metrics themselves. If these links can be coherently established, then the way is open for combat analysts to incorporate prescribed flying qualities into their pseudo-physical models through a performance scaling effect using the agility factor. These links will now be developed; the first deferred to our discussions on mission effectiveness in Section 2.3.5, the second below in 2.3.4.

## 2.3.4 The Objective Measurement of Quality

Fig 2.3.7 provides a framework for discussing the influence of an aircraft's clinical flying qualities on agility. The concept is that an aircraft's response characteristics can be described in terms of frequency and amplitude. The three lines refer to the minimum manoeuvre requirements, the normal OFE requirements and some notional upper boundary reflecting a maximum capability. Response criteria are required for the different areas on this plane - from high frequency/small amplitude characterised by bandwidth, to low frequency/large amplitude motions characterised by control power. The region between is catered for by an ADS33 innovation, the Quickness parameter (Ref 2), and is particularly germane to agility for both fixed and rotary-wing aircraft. For a given manoeuvre amplitude change (eg bank angle, speed change), the pilot can exercise more of the aircraft's inherent agility by increasing the speed of the manoeuvre change or 'attack', and hence the frequency content of his control input and the manoeuvre quickness. Likewise, the pilot can increase the manoeuvre size for a given level of attack. Increasing the manoeuvre quickness will theoretically lead to an increase in agility factor. But the maximum manoeuvre quickness is a strong function of bandwidth and control power. In ADS33C, the quickness parameter is only defined for attitude response ($\phi$, $\theta$, $\psi$) and is given by the ratio of peak attitude rate ($p_{pk}$, $q_{pk}$, $r_{pk}$) to attitude change,

$$p_{pk}/\Delta\phi, \qquad q_{pk}/\Delta\theta, \qquad r_{pk}/\Delta\psi$$

As noted by Reif, there is scope for extending this experimental agility metric to other degrees of freedom, eg incidence. Fig 2.3.8 shows derived quickness parameters for a sidestep MTE gathered on the DRA Lynx (Ref 13) and 'Configuration T509' flown on the DRA Advanced Flight Simulator (AFS) (Ref 14), the latter designed to emulate the Lynx in terms of bandwidth and control power. A quickness is calculated for every rate peak in the attitude time histories. The Lynx line on Fig 2.3.8 represents the upper boundary of all data gathered for a range of attack and sidestep sizes. The data includes the cases plotted in Fig 2.3.5 showing that at the highest agility factors/quickness, poor Level 2 ratings were awarded, ie the performance degrades rather than improves. The AFS data corresponds to a 150ft sidestep flown at the three levels of attack shown; although the roll bandwidth of the AFS configuration T509 was less than the Lynx ( ~ 3 rad/s compared with ~ 5rad/s for the Lynx), the control power was similar ( ~ 100deg/s) and similar levels of quickness were achieved by the pilots across the full amplitude range. Also shown on Fig 2.3.8 are the Level 1/2 boundaries for tracking and other MTEs from ADS33C.

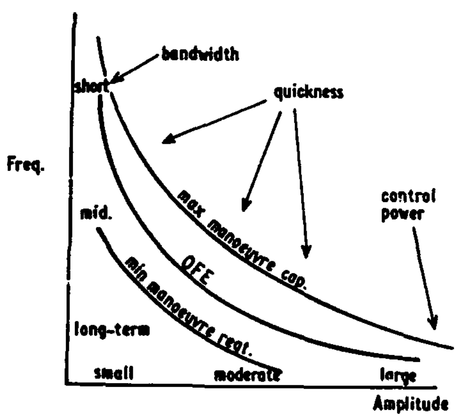



Fig 2.3.7 Response Characteristics on the Frequency-Amplitude Plane

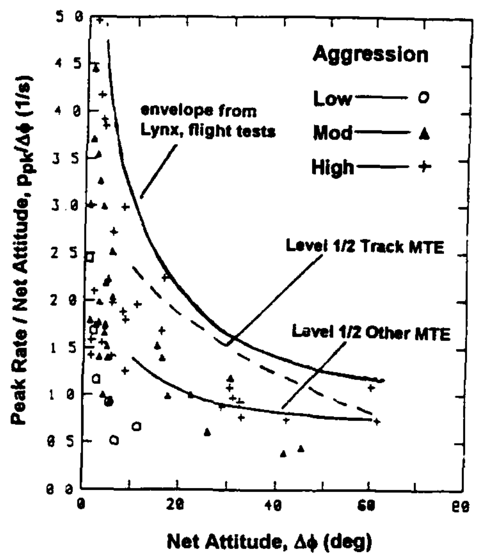



Fig 2.3.8 Roll Attitude Quickness from Sidestep Test Data in Flight (Lynx) and Ground-Based Simulation (AFS)

There are several points worth making about this data that impact on agility.

1) the shape of the quickness boundaries reflects the shape of the response capability limits on *Fig 2.3.7*. The quickness has generic value and forms the link between the bandwidth and control power but is not, in general, uniquely determined by them.

2) the result of increased attack is to increase the achieved quickness across the amplitude range.

3) the cluster of quickness at small amplitude correspond with the pilot applying closed loop control in the terminal re-positioning phase and attitude corrections during the accel/decel phases.

4) at low amplitude, the maximum achievable quickness corresponds to the open loop bandwidth except when a pure time delay is present (as with the AFS configuration), then the bandwidth is lower than the quickness.

5) the ADS33C quickness boundaries at high amplitude correspond to the minimum control power requirements of 50deg/s.

From considerations of control power, quickness and bandwidth alone, Lynx and T509 are Level 1 aircraft. In practice, at the higher attack, when the highest quickness is recorded, both are Level 2. Some of this degradation can be accounted for by simulated visual cue deficiencies with T509 and severe cross couplings with the unaugmented Lynx. The data in Fig 2.3.8 is a useful benchmark for the kind of quickness required in rotorcraft to achieve high agility factors in low speed MTEs, but it does not provide strong evidence for an upper boundary on quickness (or bandwidth and control power). The AFS rate response configuration T509 was implemented in the DRA's Conceptual Simulation Model (Ref 15) as a simple low order equivalent system of the form;

$$\frac{p}{\eta_{1c}} = K \frac{e^{-\tau s}}{\left(\frac{s}{\omega_m} + 1\right)\left(\frac{s}{\omega_a} + 1\right)} \qquad 2$$

where p is the body axis roll rate (rad/s), and $\eta_{1c}$ is the pilot's lateral cyclic stick displacement($\pm$1). $\omega_m$ is the fundamental first-order break frequency or roll damping (rad/s) and $\omega_a$ is a psuedo-actuator break frequency (rad/s). K is the steady state gain or control power (rad/s. unit $\eta_{1c}$) and $\tau$ is a pure time delay.

Fig 2.3.9 illustrates the effects of the various parameters in the CSM on the maximum achievable quickness. In particular the actuator bandwidth has a powerful effect on quickness in the low to moderate amplitude range. Maximising the actuation bandwidth and minimising delays in the achievement of maximum acceleration are in accordance with maximising the agility factor. Moreover, while this configuration has been used for helicopter-related agility research, the results are equally applicable to fixed-wing aircraft.

The sensitivity of agility factor with the parameters of the CSM is relatively easy to establish. If we consider the same bank and stop MTE discussed in the fixed-wing context earlier in this chapter, some useful insight can be gained. A pulse type control input will be assumed, although, in practice, pilots would adopt a more complex strategy to increase the agility factor. To illustrate the primary effect we consider the case where the 'secondary' time delays are set to zero (ie $\tau = 0$, $\omega_a = \infty$ ). For a roll angle change of $\Delta\phi$, the ideal time (assuming the time to achieve maximum rate is zero) is then given by ,

$$T_i = \Delta\phi / K = \Delta t \qquad 3$$

where $\Delta t$ is the control pulse duration.

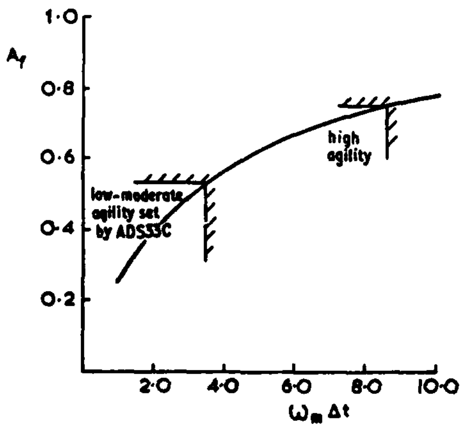
The time to reduce the bank angle to within 5% of the peak value achieved is given by,

$$T_a = \Delta t - \ln(0.05) / \omega_m \qquad 4$$

The agility factor is then given by,

$$A_f = T_i / T_a = \frac{\omega_m \Delta t}{\omega_m \Delta t - \ln(0.05)} \qquad 5$$

Fig 2.3.10 illustrates the variation of $A_f$ with $\omega_m \Delta t$. The bandwidth $\omega_m$ is the maximum achievable value of quickness for this simple case and hence the function shows the sensitivity of $A_f$ with both bandwidth and quickness.



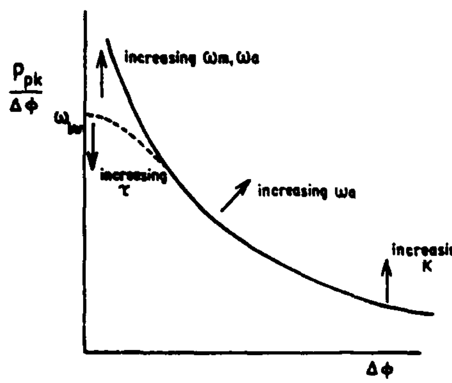




**Fig 2.3.9 Effect of CSM Parameters on Roll Quickness**

**Fig 2.3.10 Notional Variation of $A_f$ with Normalised Bandwidth**

The normalised bandwidth is a useful parameter as it represents the ratio of aircraft to control input bandwidth, albeit rather crudely. For short, sharp control inputs, typical in tracking corrections, high aircraft bandwidths are required to achieve reasonable agility factors. For example, at the ADS33C minimum required value of 3.5 rad/s and with 1

second pulses, the pilot can expect to achieve agility factors of 0.5 using simple control strategies in the bank and stop manoeuvre. To achieve the same agility factor with a half second pulse would require double the bandwidth. This is entirely consistent with the argument that the ADS33C boundaries are set for low to moderate levels of attack. If values of agility factor up to 0.75 are to be achieved, Fig 2.3.10 suggests that bandwidths up to 8 rad/sec will be required; whether this is worth the 30% reduction in task time can only be judged in an overall operational context. Such high values of bandwidth are not uncommon in fixed-wing aircraft, of course, and Fig 2.3.10 serves to illustrate and underline the different operational requirements of the two vehicle classes.

This simple example has many questionable assumptions but the underlying point, that increasing key flying qualities parameters above the ADS33C boundaries has a first order effect on task performance, still holds. But it provides no clues to possible upper performance boundaries set by flying qualities considerations. As stated earlier, ADS33C does not address upper limits directly. Also, practically all the upper boundaries in Mil Std 1797 are related to the acceleration capability of the aircraft. As noted earlier, there are tentative upper limits on pitch attitude bandwidth, but it is suspected that these are actually a reflection of the high control sensitivity required to maintain a defined level of control power, rather than the high values of bandwidth per se. Control sensitivity itself ($rad/s^2.inch$) is a fundamental flying qualities parameter and is closely related to the pilot's controller type; while some data exists for helicopter centre and side sticks, more research is required to establish the optimum characteristics including shaping functions. Mil Stan 1797 provides a comprehensive coverage of this topic for fixed-wing aircraft, rather more as guidance than firm requirements.

Another potentially fruitful avenue appears to lie in the extension of the quickness parameter to the acceleration phase of an MTE. The fixed wing CAP already suggests this as the ratio of pitch acceleration to achieved normal 'g' (effectively, pitch rate). The DRA CSM used in the AFS trials offers a good example to explore and develop this concept of rate quickness. Setting the pure delay term in the CSM to zero for this study, the magnitude and time constant of the peak roll acceleration, for a step control input, can be written in the form;

$$\dot{p}_{pk} = \frac{K\omega_m}{\gamma} e^{-\omega_a t} \eta_{1c} \qquad 6$$

$$\omega_a t = \frac{\log\gamma}{1-\gamma}, \qquad \gamma = \omega_m/\omega_a \qquad 7$$

The rate quickness can then be written in the form,

$$\frac{\dot{p}_{pk}}{\Delta p} = \frac{\omega_m}{\gamma} e^{\frac{\log\gamma}{1-\gamma}} \qquad 8$$

This function is plotted in normalised form in Fig 2.3.11.

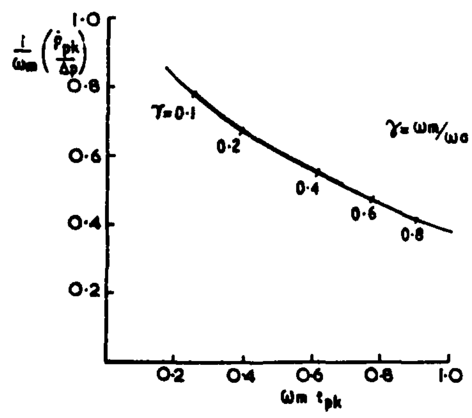



**Fig 2.3.11 Variation of Rate Quickness with Acceleration Time Constant**

During the AFS handling qualities trial described in Ref 14, the lag bandwidth $\omega_a$ was set at 20 rad/s to satisfy the pilot's criticism of jerky motion. This gave a $\gamma$ of about 0.5 at the highest bandwidth flown (T509). Corresponding values of rate quickness and time to peak acceleration were 0.5 and 0.7 respectively, both relative to the natural aircraft bandwidth, $\omega_m$. Intuitively, there are likely to be upper and lower flying qualities bounds on both of these parameters. Hard and fast may be as unacceptable as soft and slow, both leading to low agility factors; the opposite extremes may be equally acceptable when referred to the maximum quickness. This suggests closed boundaries delineating the quality levels on the Fig 2.3.11 format. Clearly, more systematic research and data capture are required to test and develop this hypothesis further.

The results of this objective quality analysis indicate that the flying qualities parameters are suitable for quantifying agility beyond the minimum levels set by the standards. The quickness, for example, is a natural measure of agility, increasing with manoeuvre attack, and spanning the low frequency/high amplitude to high frequency/low amplitude range of manoeuvre kinematics. Upper limits on flying qualities may, however, be better expressed in terms of acceleration-based parameters, rather than the rate-based parameters more commonly found in the flying qualities standards. Upper limits for small amplitude motions appear to be well catered for by control sensitivity in the various axes. For larger motions, there is a significant gap; some of the ad-hoc parameters in Mil Standard 1797, eg CAP, do point to a possible generic approach. ADS33C does not address upper limits at all. The quickness concept has been extended to the acceleration response with a view to bridging this gap.

### 2.3.5 The Subjective Measurement of Quality

Flying quality is ultimately determined by pilot subjective opinion. The 'measurement scale' and the understanding for this continue to stimulate vigorous debate but the Cooper-Harper handling qualities rating (HQR or CHR) scale provides the most widely accepted standard. The operational benefit of good flying qualities has never been properly quantified using the HQR approach, however. But the benefits to safety have been addressed in References 16 and 17, using the Cooper-Harper pilot rating scale as a metric (Fig 2.3.1). These references consider the pilot as a vital system component who can fail (be stressed to failure) in an operational context. The authors point out that if a normal distribution of ratings is assumed, then the probability of control loss, $P_{loc}$, can be calculated for various mean ratings and dispersions (Fig 2.3.12). $P_{loc}$ is the probability of obtaining a rating greater/worse than 9.5, which in turn is simply proportional to the area under the distribution to the right of the 9.5 rating.

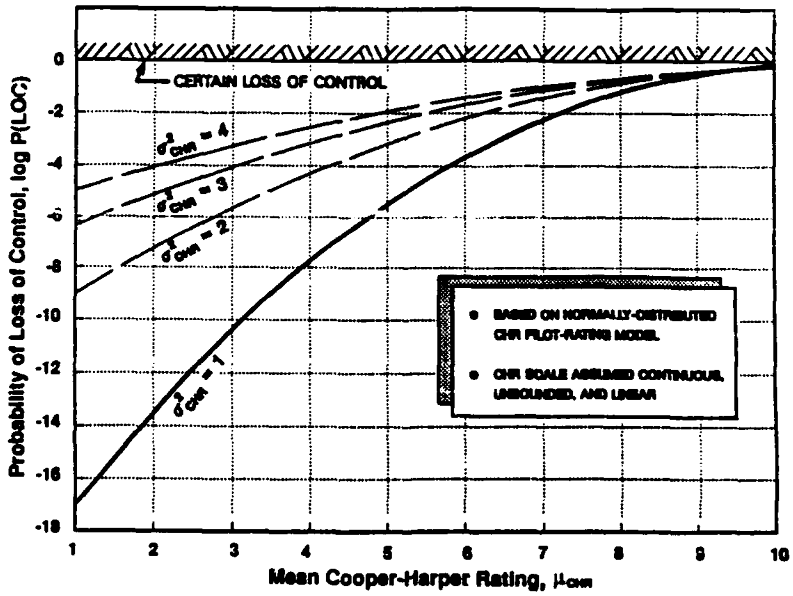



**Fig 2.3.12 Relationship Between Mean CHR (HQR) and $P_{loc}$**

Thus the probability of **flight failure**, due to flying qualities deficiencies can be estimated. For the case studied in Ref 16 and depicted in Fig 2.3.12, operating a Level 1 aircraft can be seen to reduce the probability of a crash by an order of magnitude relative to a Level 2 aircraft. This result immediately raises the question - what is the probability of **mission success or failure** and can the same comparisons be made between aircraft with different mean flying qualities?

Fig 2.3.13 shows a notional distribution of ratings, with the regions of desired, adequate and inadequate performance clearly identified. The desired and adequate levels can be considered as reflecting varying degrees of mission (task element) success while the inadequate level corresponds to mission (task element) failure. Effectively the mission is composed of a number of contiguous MTEs, each having a virtual HQR assigned on the basis of performance and workload that the situation demands and allows respectively. If a particular MTE was assigned a Level 3 rating, then the pilot would either have to try again or give up on the particular MTE. Loss of control has obvious ramifications on mission success. The probability of obtaining a rating in one of the regions is proportional to the area under the distribution in that region. Note that, as discussed in Refs 16 an 17, we include ratings greater than 10 and less than 1 in the analysis. The rationale is that there are especially good and bad aircraft or situations, whose qualities correspond to ratings like 13 or minus 2. However, the scale enforces recording them as 10 or 1.

Note too, that the scatter produces, even with a good mean rating, a large probability of merely adequate performance and even a finite probability of total loss of control and crash. We have said in the Introduction to this Chapter that flying qualities are determined by the synergy between internal attributes and external influences. It follows then that sources of scatter originate both internally and externally. Internal sources include divided attention, stress and fatigue, pilot skill and experience. External sources include atmospheric disturbances, changing operational requirements and timelines, threats etc. The flying qualities community has done much to minimise scatter by careful attention to experimental protocol (Ref 18) but, in operational environments, the effective pilot rating scatter is omnipresent.

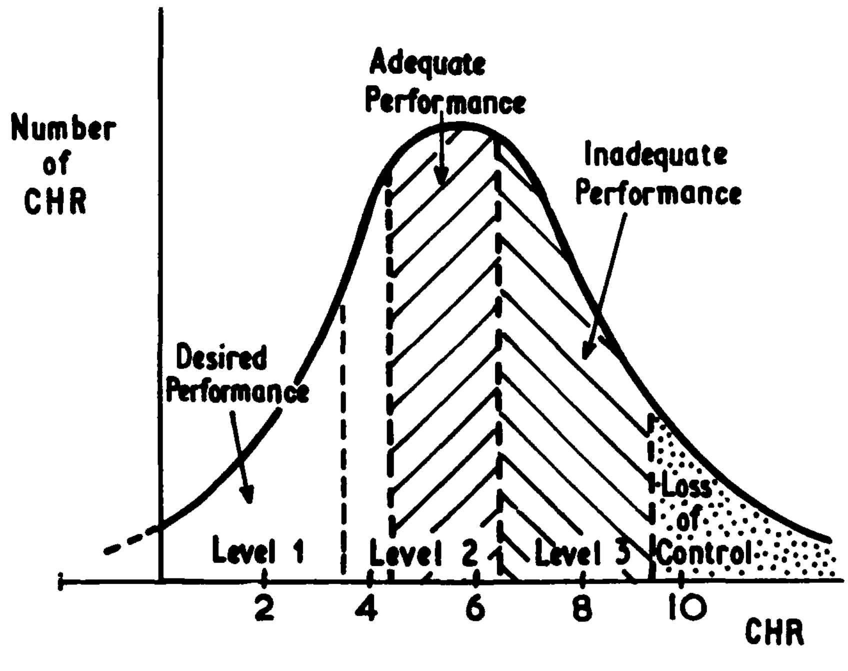



**Fig 2.3.13 Notional Distribution of Pilot Handling Qualities Ratings for a Given Aircraft**

Fig 2.3.14 shows the probability of obtaining ratings in the various regions when the standard deviation of the ratings is unity. This curve, which we have labelled as preliminary, has some interesting characteristics. First, the intersections of the lines fall close to, or exactly at, the ratings 4.5, 6.5 and 9.5, as expected. Also it turns out that for a mean rating of 7, the probability of achieving inadequate performance is, of course, high, and we can also see that the probability of achieving desired performance is about the same as that for loss of control - about one in a hundred. Improving that rating to 2, lowers the probability of loss to $10^{-13}$ (for our purposes zero) and ensures that performance is mostly at desired levels. Degrading the mean rating from 2 to 5 will increase the chances of mission failure by three orders of magnitude.

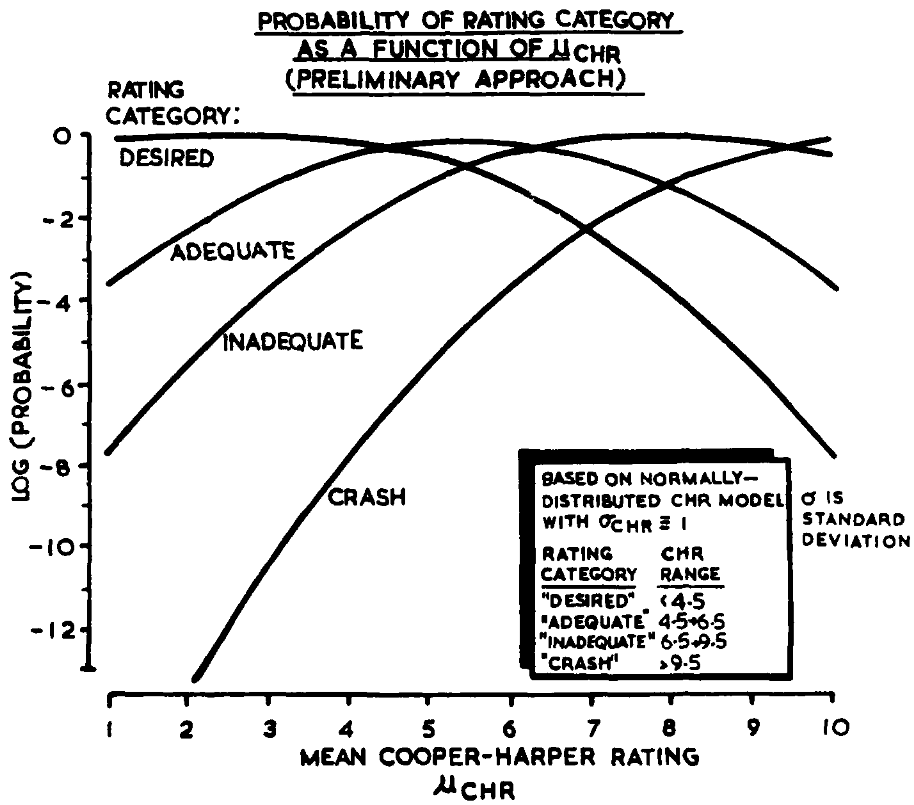



**Fig 2.3.14 Relationship Between Mean CHR (HQR) and Probability of Mission Success, Failure or Crash - Preliminary Results**

We describe these results as preliminary because we assume that there is a rational continuum between desired performance, adequate performance and control loss. For example, desired and adequate performance may be represented by discrete touchdown zones/velocities on the back of a ship and loss of control might be represented by, say, the edge of the ship or hanger door. On a smaller ship (or bigger helicopter, for example), the desired and adequate zones may be the same size as on the larger vessel, which puts the deck-edge closer to the adequate boundary, or represent a similar fraction of the deck size, hence tightening up the whole continuum. This raises some fundamental questions about the underlying linearity of the scale. With the servo-model of piloting behaviour, for example, we can always define a desired level of flight path task performance so demanding that, whatever the aircraft attitude bandwidth, pilot induced oscillations will result, leading to level 3 ratings.

Though these questions remain, pilot rating and mission success or failure are powerfully related through the preliminary data in Fig 2.3.14. Flying qualities alone can determine whether operational agility is flawless or whether control is lost.

### 2.3.6 Including Flying Qualities Effects in Combat Models

The results highlighted in this Chapter suggest ways by which the effects of flying qualities can be incorporated into unmanned combat mission simulations. Such models are regularly used to establish the effectiveness of different weapon system attributes or tactics, but the human element is usually absent for obvious reasons. The aircraft are therefore assumed to have perfect flying qualities and the models are often configured to ignore the transient responses, effectively assigning an agility factor of unity to each manoeuvre change or MTE. The impact of these assumptions is twofold; first, there is no way that flying qualities or their enabling technologies can be included in the trade studies conducted with such models. Second, the implied perfect flying qualities may give a false impression of the importance or the value of mission performance enhancements. The key steps to embodying the key flying qualities effects are suggested as follows;

1) through objective design and assessment, establish the level of flying quality and hence the effective mean HQR for a configuration,

2) describe the mission in terms a series of contiguous MTEs, selectable in the same way that set - piece manoeuvres are in combat models,

3) establish a MTE hazard weighting on the basis of threat, divided attention and other internal/external factors, that will define the effective virtual HQR for the MTE. This will vary as the mission develops,

4) establish a time scaling for each MTE, on the basis of the maximum achievable agility factor,

5) overlay the time scaling on the mission profile; there will be an option for each MTE to fly at reduced agility factor with level 1 virtual HQR or to fly at the higher agility factor at a poorer HQR.

Improvements or degradations in flying qualities can then explored through variations in the achievable agility factors and mean HQR for the aircraft and can be linked directly to the enabling control technologies. There are, of course, some fundamental questions associated with this approach. How can we assign the mean rating and the standard deviation? How do we classify the hazards resulting from the various degrading influences? How are the maximum agility factors derived? These and others will need to be addressed if this approach is to be taken further; the benefits are potentially high however, both in terms of clarifying the value of active control to effectiveness and, conversely, establishing the cost of flying qualities limitations to operational agility.

### 2.3.7 Conclusions and Recommendations

Operational agility is a key attribute of any weapon system and its subsystems from sensors, through the airframe elements and pilot, to the primary mission element, eg weapon. The total system can only be as agile as its slowest element and maximising the concurrency within the subsystems is a key method for enhancing agility. The focus of this Chapter is the airframe and its primary enabling attribute - its flying qualities. The adequacy of existing flying qualities criteria for providing agility is addressed along with the benefits to agility of good flying qualities and the penalties of poor flying qualities. The following principal conclusions can be drawn.

1) Existing flying qualities criteria provide a acceptable and necessary framework for describing and quantifying agility; the quickness parameter stands out as a useful agility metric and should be extended beyond the current rotary-wing attitude response requirements to flight-path variables and fixed-wing applications. However, the existing quality boundaries are only minimum standards and do not reflect or quantify the desirable characteristics at high performance levels. Indeed, there are very few boundaries defined that set upper limits on usable performance.

2) The agility factor provides a measure of usable performance and can be used to quantify the effects of flying qualities on agility. Rotary-wing research has shown that agility factors up to 0.7 can be achieved with current aircraft types operated with high performance margins, but handling deficiencies typically lead to HQRs in the poor level 2/level 3 region. Moreover, the degradation from Level 1 to 3 is rapid. High agility factors achievable with Level 1 flying qualities should be a goal for future operational types.

3) Extensions of the ADS33C innovation, the quickness, into the acceleration response is suggested as a potentially useful parameter for setting flying qualities limits on performance. Flight and simulation data needs to be gathered and analysed systematically to test this hypothesis.

4) It is argued that even a Level 1 aircraft 'on paper' will degrade to level 2 and 3 in unfavourable situations. In this context, a probabilistic analysis can be used to highlight the benefits of improved flying qualities on operational agility and mission effectiveness. Operating a Level 2 aircraft is shown to increase the chances of mission failure by three orders of magnitude, compared with a Level 1 aircraft. The results are preliminary and dependent on a number of underlying assumptions, but indicate a powerful relationship. Experimental results are needed to substantiate the results; these could include learning runs and trials with varying degrees of external influences.

5) Considering the mission as a series of contiguous mission task elements enables the agility factor and probability of success/failure to be overlayed on non-piloted combat mission simulations. This should allow flying qualities to be included in such exercises and flight control technologies to be integrated into mission effectiveness trade studies.

6) The key to ensuring that future projects are not susceptible to performance shortcomings from flying quality deficiencies would appear to be in the development of a unified specification for flying qualities and performance, with a clear mission orientation in the style of the new flying qualities requirements.

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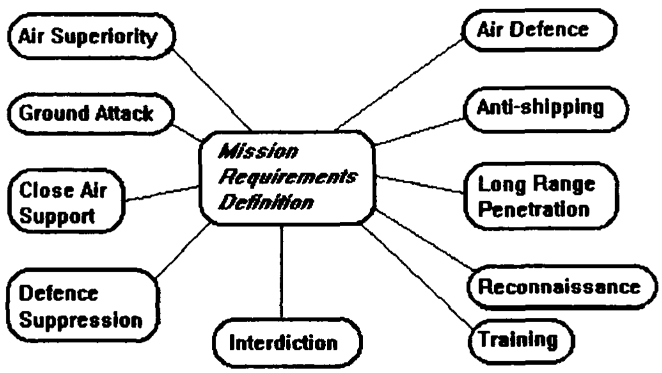
## 2.4 Design for Airframe Agility

### 2.4.1 Introduction

In this section of the report, consideration is given to how the various requirements and constraints are combined such that an agile airframe results. In doing this, it is essential that the overall balance of the factors which contribute is addressed. This requires engineering awareness and assumptions regarding the various systems capability, since the latter will have a major influence on the level of airframe agility required.

Design for airframe agility starts with an understanding of the requirements for the vehicle or, more precisely, of the roles which the vehicle must fulfill, figure 2.4.1. Clear understanding of the customers' intended use will simplify the process and should reduce the design cost, whilst generating a better quality product.

**Figure 2.4.1: Relation of Roles and Mission Requirements**




The process of designing an airframe to be agile starts with determining the optimum balance amongst the requirements dictated by:-

* Mission Performance
* Supersonic Cruise and Manoeuvre
* Transonic Manoeuvrability
* Low Speed Flight Characteristics
* Signature
* Structural Characteristics
* Flight Control System Complexity
* Weapons Carriage
* Safety/Airworthiness
* Avionics
* Cost Effectiveness

Historically, airframe agility has tended to be a fall-out of the design process, rather than a specific goal. The description "agile" has often been mistakenly used to describe aircraft which were deficient in their handling, due to their lack of stability. The Sopwith Camel of World War I was such a vehicle; it had a reputation for agility but was lethal in the hands of a novice. Similar examples can be found in later conflicts, even up to the present day.

The next section will attempt to address the question " How to design for airframe agility?" It will illustrate the engineering trade-offs that have to be established. Vehicle systems have to be accounted for, but they are not

specifically addressed here but in later chapters. To answer the question, it is necessary to look at the whole process to determine where airframe agility might influence the decisions.

The aspects which will be considerer may be grouped as:-

* Configuration layout, which dictates the manoeuvrability and performance
* Structural design, which provides the upper limits on manoeuvrability
* Stability and Control, Controllability and Flight Controls System Design which relates Handling Qualities design criteria, stability criteria, response and quickness
* Powerplant integration, which relates to performance, control and which for rotary wing vehicles, may dictate the limit on manoeuvrability.

### 2.4.2 Configuration and Aerodynamic Design

The design process can be categorised under three headings, having started with the Mission Requirements, these are the three "S's", ie.

* **Shape**
* **Structure**
* **Systems**

Configuration and aerodynamic design relate to shape and structure. In this section, shape is the primary interest; structure will be dealt with in the following section. Systems are considered in Chapters 3 and 4.

The features of the mission requirement which define shape and size of an aircraft are:-

| SHAPE | SIZE |
|---|---|
| How fast? | What payload? |
| At what altitude? | How far? |
| How manoeuvrable? | |
| From what runways? | |

The first question, for fixed wing designs, must be "Is there a supersonic requirement?" This has a major influence on all that follows, impacting on manoeuvrability and agility. The second question must then relate to the angle of attack range that is required, as potentially large pay-offs may result from the combination of a number of technologies relating to this flight regime. The third question will be "Is there a signature requirement" and that may even be the first, depending on the foreseen role for the vehicle.

The process contains a number of iterative loops, the first relating size and shape. At the end of this, a conceptual design capable of meeting the primary requirements will exist. Transient agility levels will be dictated by the manoeuvrability and performance levels which result from this first loop.

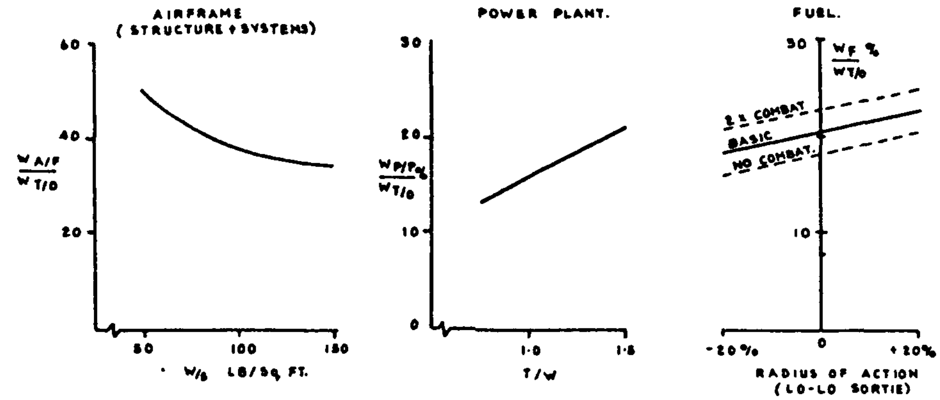
Trade studies establish rates of exchange which enable the differing criteria to be evaluated against each other. Often, such studies are automated and feature optimising routines which enable the design options to be established more quickly. Figure 2.4.2 illustrates the individual trades which might result from such a study.

Maximum lift is strongly dependent on wing planform. It dictates turning performance, unless the use of post-stall technologies is considered for low speeds. However, the thrust limited turn capability, the sustained turn, is dictated primarily by span loading and thrust to weight ratios. High levels of airframe agility favour low span loadings.

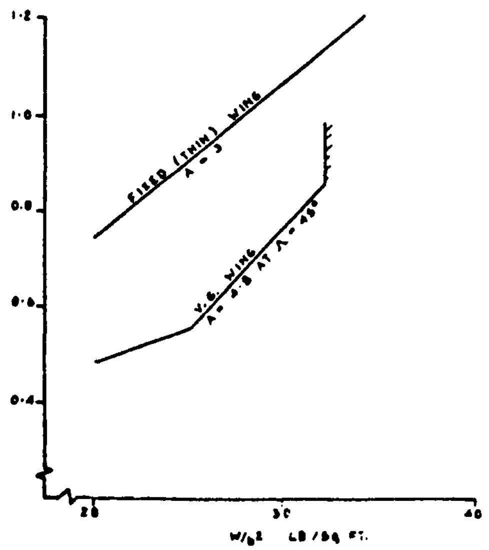
**Figure 2.4.2: Examples of Typical Rates of Exchange**

VARIATION OF AIRFRAME, POWER PLANT AND FUEL FRACTIONS
WITH WING LOADING, T/W. RATIO AND RADIUS OF ACTION.

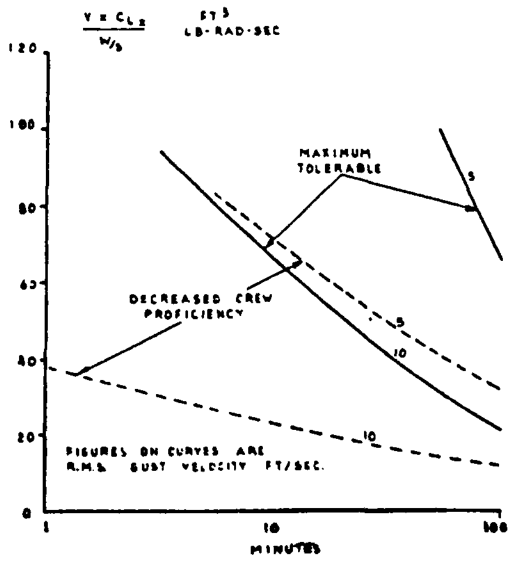
$$\frac{W_{AF}}{W_{T/O}} + \frac{W_{PP}}{W_{T/O}} + \frac{W_{F}}{W_{T/O}} + \frac{W_{FIXED}}{W_{T/O}} = 1$$




VARIATION OF THRUST/WEIGHT RATIO
WITH SPAN LOADING, TO MEET A
SUSTAINED MANOEUVRE REQUIREMENT




GUST RESPONSE·
DURATION OF TOLERABLE EXPOSURE TIME AS
A FUNCTION OF TURBULENCE LEVEL AND
AIRCRAFT RESPONSE PARAMETER

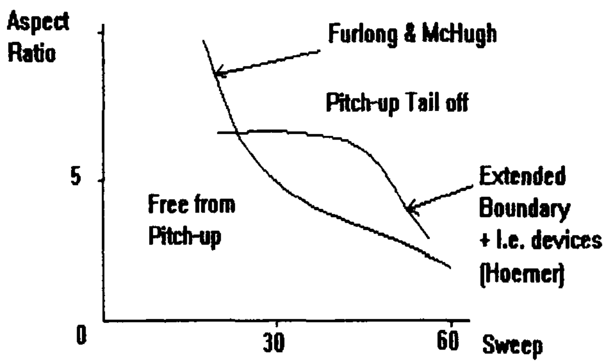


Before finalising the shape of the wing, it is necessary to consider the other drivers, such as airfield performance and gust response. STOL operations and combat manoeuvrability favour low wing loading and, possibly, effective high lift devices. Which sizes the wing could depend on the type and effectiveness of the high lift devices. Extreme short landing requirements may dictate powered lift, if the cost and complexity can be justified. Gust response tends to require low lift curve slope, ie. high sweep, combined with a high wing loading, completely contra to the needs of agility of the airframe, at least as conventionally thought of.

On top of this, the latest requirements will tend to feature a signature level which has to be achieved and this can dictate the wing geometry with regard to sweep, taper and leading edge sharpness, all of which impact on agility and manoeuvrability.

Whilst performance tends to drive the wing design, stability and control may place restrictions on the combinations of geometry which would be considered. Typical are the limitations due to stall and pitch-up. Figure 2.4.3 illustrates boundaries derived from test data which provide guidelines as to the combinations of sweep and aspect ratio which avoid pitch-up. The boundaries are indicative and exceptions will exist on either side.

**Figure 2.4.3: Pitch-Up Boundaries**




With the conceptual design complete, at least for the moment, the second design iteration can begin. This will include a number of parallel and interactive studies from which a detail baseline will result. One result of this loop may be that the first iteration has to be repeated.

The second sizing loop should contain:-

i) The initial wing design, combining the compromises of subsonic, transonic and supersonic cruise and manoeuvre performance, including any necessary high lift devices.

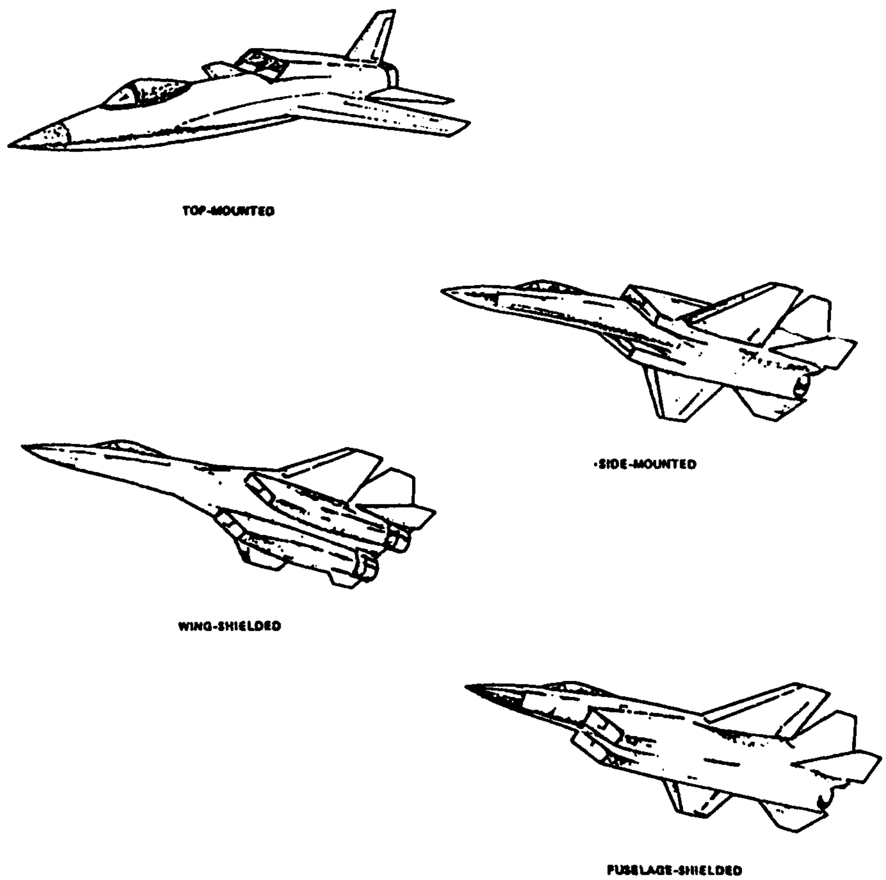
Stall behaviour, dependent on sweep and leading edge radius, may provide restrictions, particularly if a sharp leading edge is required. References 4 to 7 provide further details. The progressiveness of the flow breakdown and the ability to control the aircraft through the transition from attached to separated flow will determine whether or not the stall is limiting. The effects of the body, in particular the nose and intakes, can be very significant, as outlined in references 8 to 12.

ii) The initial inlet design, including the determination of the location, capture and throat areas, the inlet profile and type. This activity will also determine the geometry of any intake diverter. Figure 2.4.4 illustrates the choices available.

iii) The fuselage profiles to provide minimum transonic and supersonic drag, whilst providing the necessary volume for fuel, engines, equipment and crew.

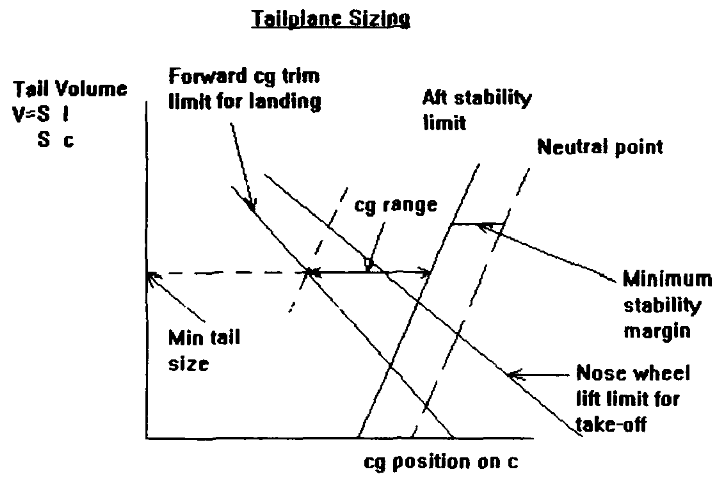
iv) Control surface dcsign to ensure the necessary levels of control power are provided over the flight envelope.

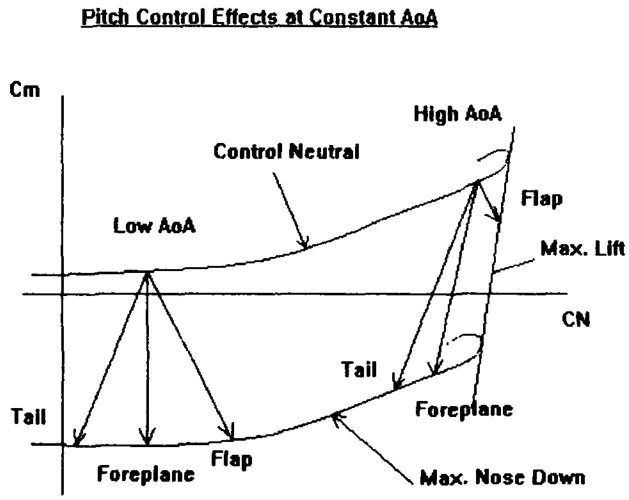
**Figure 2.4.4: Choice of Inlet Layout and Position**




Pitch control surface design is dictated by three fundamental aspects, stabilisation of the aircraft, trim and provision of adequate control power to meet manoeuvre demands, nosewheel lift or pitch recovery from high angles of attack. Figure 2.4.5 shows a typical sizing study. A key element of this is deciding what level of pitch stability can be tolerated. This is dictated by consideration of performance, via trim drag, combined with the level of technology assumed for the flight control system. These latter assumptions are crucial for aircraft featuring relaxed stability and fly-by wire FCS designs with Control Configured Vehicle concepts.

**Figure 2.4.5: Control Surface Sizing**

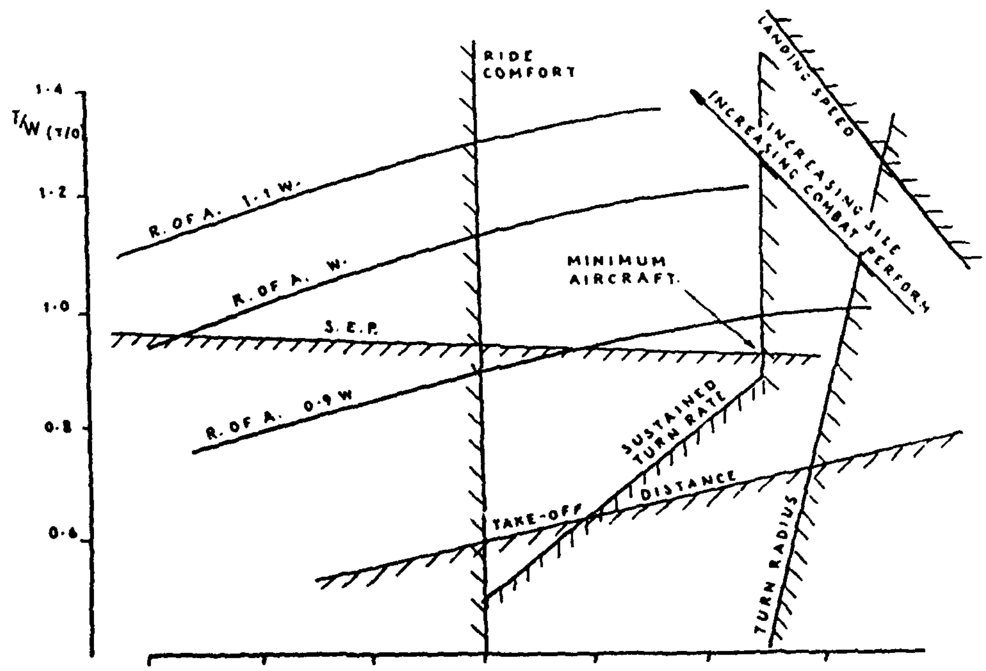



Combining these criteria, a sizing diagram such as those shown in figures 2.4.6 and 2.4.7 results. These illustrate the design window available, giving the minimum airframe capable of meeting the prescribed tasks.

Airframe agility is defined, to the first order, by this choice of configuration. From here on, the basic levels of agility attainable have been determined. In order to get the maximum from the chosen configuration, it is necessary to consider the second order terms and their interaction. These are addressed further in section 2.4.4.

Figure 2.4.6: Aircraft Sizing Plot - Example 1



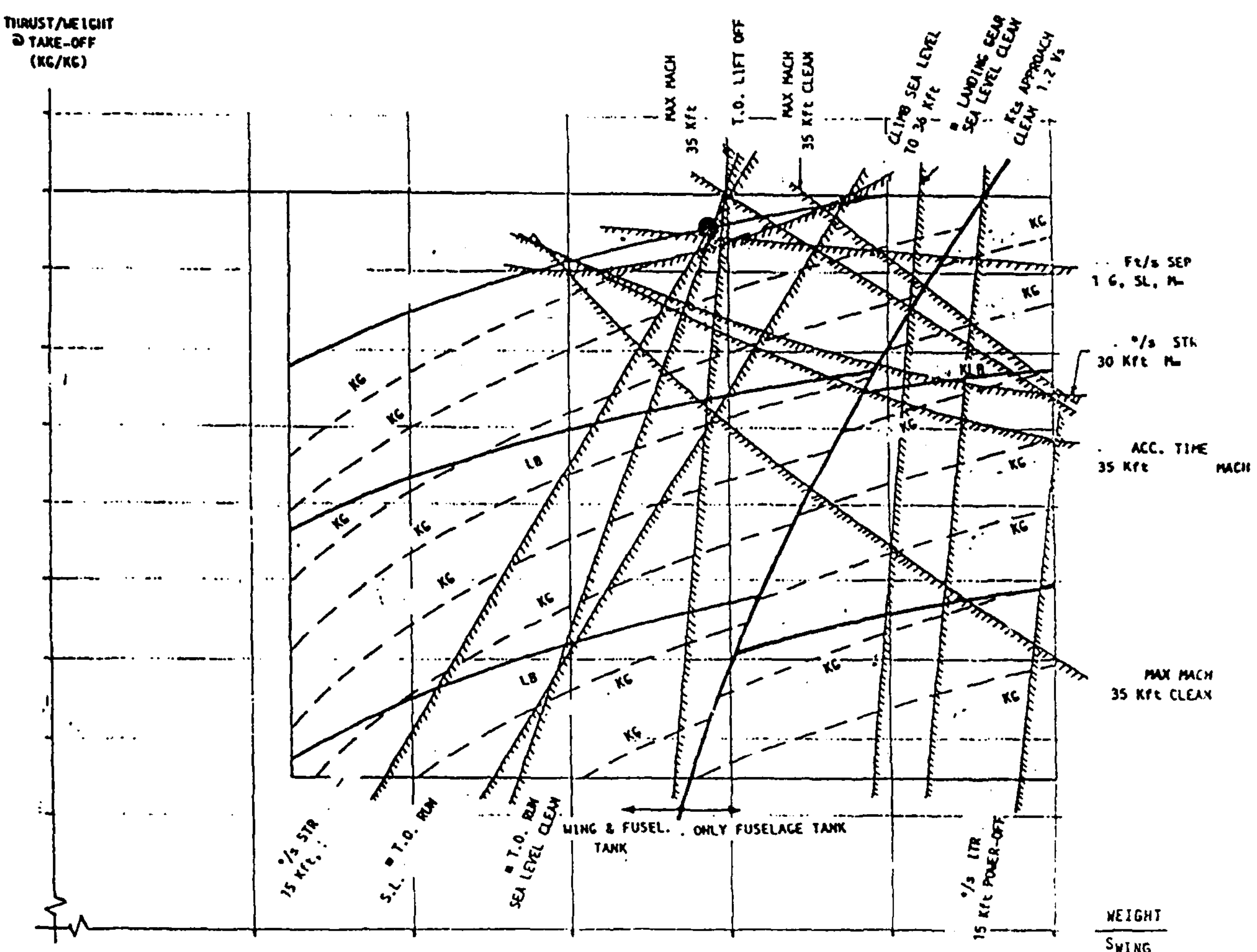


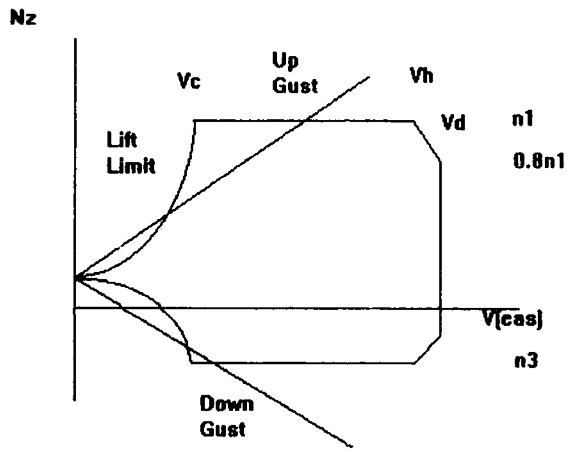

Figure 2.4.7: Aircraft Sizing Plot - Example 2

**2.4.3 Structural Design**

Structural design is one of the major considerations in vehicle sizing. In this section, the intention is examine how the structural design relates to and impacts on the airframe agility.

To do this, it is necessary to assume that the design normal acceleration levels have been determined as part of the sizing first loop and that the trades between structural capability and the vehicle systems has already been determined. With this information and the mission requirements, the design loading envelope can be produced, complying with structural design criteria dictated usually by the customer, see references 13 and 14. Figure 2.4.8 shows a typical design envelope. The design normal acceleration levels and their associated limit loads provide upper limits on the airframe agility.

**Figure 2.4.8: Typical Structural Design Envelope**




Typically, the design normal acceleration is set with the physiological limits of the crew in mind as well as the impact that the associated loads may have on vehicle mass and/or fuel fraction.

With this established, the next factors which relate to the airframe agility derive from the asymmetric manoeuvre capability, ie the roll performance, particularly in loaded rolls or rolls performed at other than 1g for entry. Conventionally, loaded rolls were provided for at up to 80% limit load but, with the advent of FBW and "carefree handling", the FCS is expected to tailor the response automatically. Under such circumstances, the limit on the airframe agility may well be determined by the structural capability to withstand the loads generated or by the ability to provide sufficient yaw control to co-ordinate the roll. It is therefore essential that the flight mechanics handling targets and the structural design are properly balanced. Figure 2.4.9 illustrates a balanced design, where these considerations have been matched. The consequences of such a design are illustrated in figure 2.4.10, which has been generated for a typical modern combat aircraft for which carefree handling was a design objective, both sub and supersonic.

**Figure 2.4.9: Typical Roll Performance as a Function of Angle of Attack and Normal Acceleration**

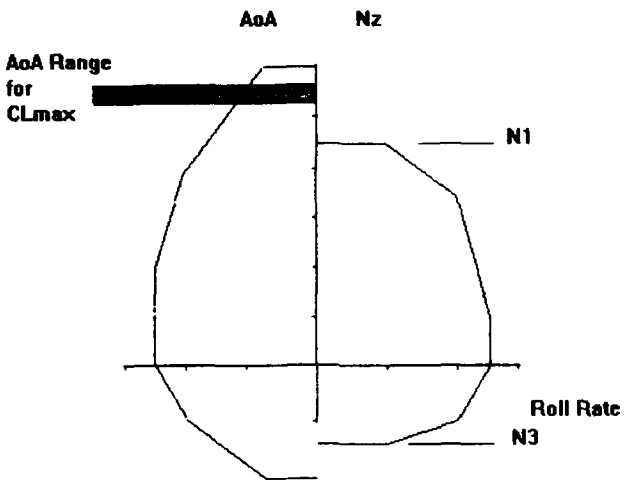
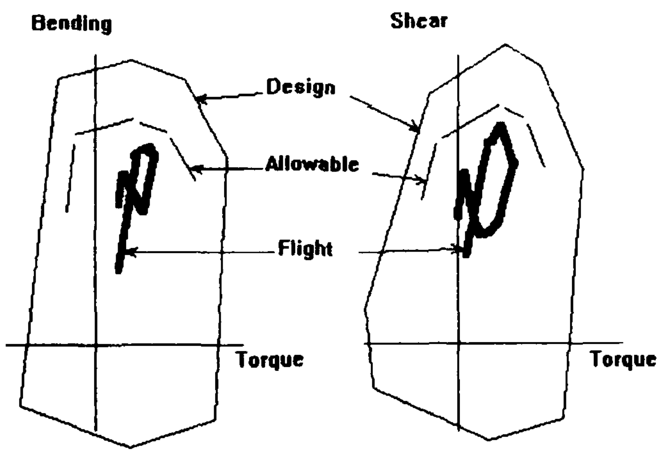



**Figure 2.4.10: Typical Load Monitor Plots Taken From Flight Trials**




Whilst steady roll conditions are often used to characterise a vehicle's airframe agility, the rate at which the roll can be achieved is as important to the pilot. This will affect the ability to roll and stop at the desired bank angle, reverse turns, jink, etc. Design for roll acceleration capability will often influence the structural design, setting aeroelastic stiffness requirements or determining the required hinge moments for the surface actuators. Reference 35 provides relevant reading relating to structural design optimisation and includes the increasingly important aspect of fin design at high angles of attack.

Thin wings are usually stiffness designed rather than strength designed and these roll rate and acceleration criteria will often edsign the wing torsion box.

Upper limits on roll acceleration may come primarily from one of two areas, ie. the structural capabilty and control effectiveness or from the generation of excessive lateral acceleration at the position of the pilot's head. This latter will tend to dominate if the pilot sits with his head significantly displaced from the roll axis of the aircraft.

Similarly, pitch acceleration must be considered. Few parts of the vehicle will be designed directly by the pitch acceleration but it can have the effect of sizing controls, particularly for recovery from high angle of attack when rolling. Under these conditions, it essential that sufficient pitch acceleration capability exists to counter the inertial effects and provide a control margin. As with roll acceleration, too high a value is to be avoided, especially associated with high g rates, when "g-loc" may become a consideration.

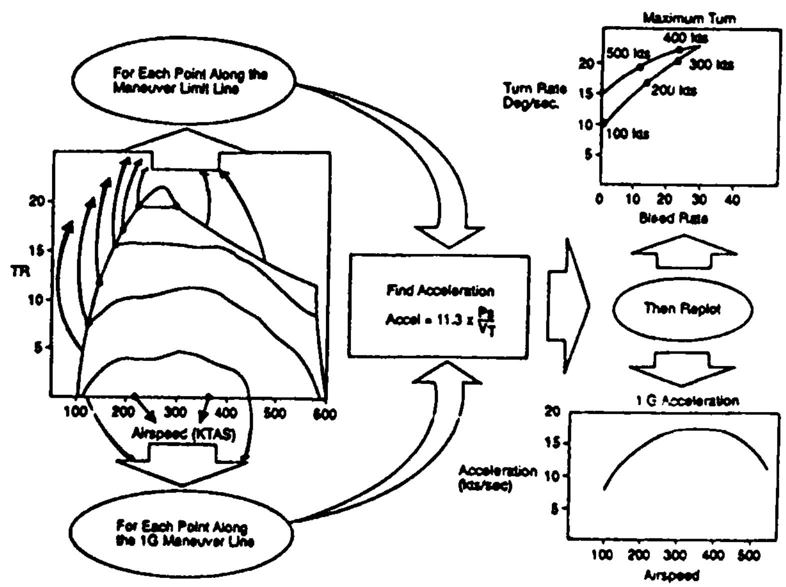
Getting the structural to flight mechanics balance right is essential if excessive mass, over or undersized actuation systems and the impact of excessive hydraulic power drains on the vehicle propulsion unit are to be avoided.

### 2.4.4 Stabilty & Control, Controllability and Flight Control System Design

It is the stability and control characteristics combined with the flight control system design that probably contribute most to whether a vehicle is regarded as agile or not. This focusses on the handling, the poise and quickness of response together with the accuracy of control achieved. There have been cases where superior handling and controllability have enabled aircraft with lesser performance to overcome "superior" opponents. The F-5 is classic in this respect, hence its use for aggressor training.

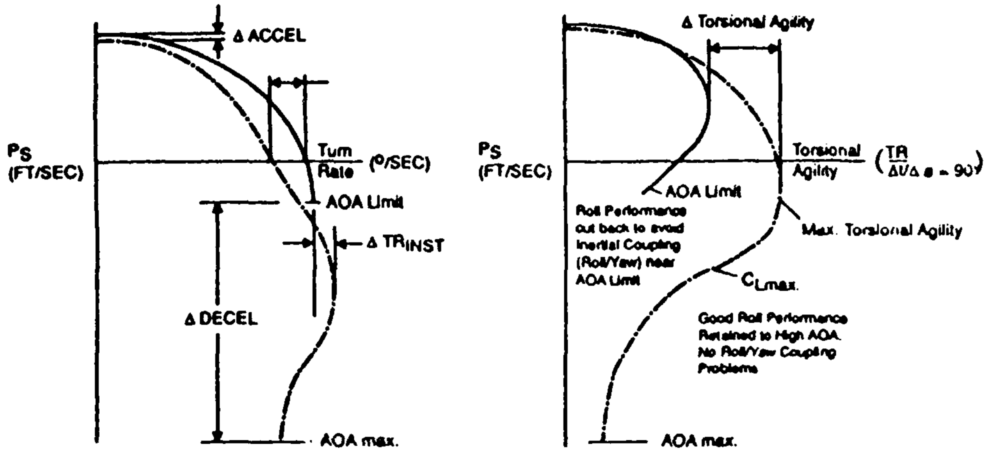
This sort of experience gave birth to agility as a concept and the attempts to quantify it. Figures 2.4.11 and 2.4.12 show examples of metrics which attempt to quantify such effects (see references 16 to 19 and Section 2.3 for much more detail). Clearly, the transient and experimental agility metrics outlined in section 2.3 will assist the designer in his task.

**Figure 2.4.11: Dynamic Speed Turn (DST) Plots**



For this design loop, one of the most important questions to address is does the vehicle have a requirement for "carefree handling" or not and, if so, does this imply the use of very high angles of attack in the post-stall regime. Clearly, a trade study has to be performed to assess cost versus effectiveness fo the options which result. An alternative to "carefree handling" is the concept of "graceful degradation", where the behaviour is allowed to degrade progressively in a way which tells the pilot exactly where he is in relation to any loss of control. Such choices may impact on the configuration and will certainly influence control power requirements to the extent that additional effectors, such as thrust vectoring or nose vortex control are necessary.

**Figure 2.4.12: Turn Rate and Torsional Agility Criteria**




Handling qualities criteria currently provide the majority of design criteria relating to both flight mechanics and flight control law design. They provide an excellent starting point, but care is required as they may not give the whole picture.

### 2.4.4.1 Stability & Control Criteria

The S&C criteria used in the configuration design process usually stem from the handling requirements. They may impact on performance and manoeuvrability directly, for example by determining the levels of instability that the flight control system can cope with. This can impact on trim drag, by not allowing the performance optimum to be achieved. In such a case, the designer may be forced to move the wing. In all cases where high levels of augmentation are required, then the upper limit will be determined by the maximum gain of the FCS and the associated phase lags.

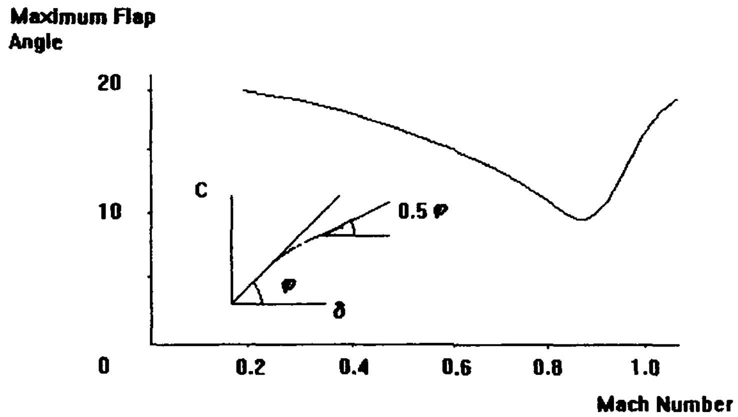
A wide range of criteria have been developed for assessment of S&C characteristics over the years. Each has contributed to understanding and some, such as $Cn_{\beta DYNAMIC}$ and LCDP, have stood the test of time, even thought they are only indicative and do not tell the whole story. Engineers have learned to live with them and interpret them. With highly augmented systems, these terms have to be used with care as the effect of the damping terms can be very significant; indeed, the FCS can modify these terms totally, although they do retain their meaning. References 21 to 24 provide further detail of the criteria which may be applied.

Experience is leading to an as yet unwritten criteria relating to the linearity of the basic aerodynamics. The ideal is for linear stability characteristics and monotonic control effectiveness, both of which ease the FCS design and cost. However, there has been a trend in the opposite direction, due to the capability of digital computers and a belief that

"the FCS can take care of it". This is in part the truth, but in the end, the resultant handling is only as good as the basic aerodynamics allow. A good FCS can mask poor aerodynamics, to a point; if that is reached then the FCS tends to let go with a bang!

Control linearity can influence airframe agility. Trailing edge controls become very non-linear in the transonic regime at increasing deflection and care has to be taken to avoid extreme non-linearity or even reversal. Figure 2.4.13 illustrates a criterion which can be used to ensure that, when used as primary controls for both pitch and trim (and roll), sufficient control effect remains at the limiting conditions.

**Figure 2.4.13: Maximum Allowable Trailing Edge Angles For FCS Stability and Control Requirements**




**2.4.4.2 Handling Qualities**

The handling qualities design criteria, examples of which may be found in references 14 and 25, are major drivers for the design of the FCS. They can provide constraint on the maximum levels of airframe agility, as indicated in section 2.2. More aggressive use of the controls may result in degraded handling to the point where the vehicle may become unsafe.

As noted in reference 26, handling qualities criteria are applied to small amplitude motions of the aircraft and may be either inapplicable or, worse, misleading when applied to the large amplitude motions which would generally be associated with airframe agility. Formal criteria for large perturbation motions are few, certainly for fixed wing aircraft, although there are a few moderate amplitude criteria for rotorcraft included in their requirements (reference 27).

The designer must decide over what range of the intended flight envelope the handling qualities criteria must apply. Whatever is decided, it is essential to check the behaviour in gross manoeuvres, using both piloted and non-piloted simulations. The effects of non-linearities in the system, ie. aerodynamic, actuation, filters, compute delays or structural notches, must be included as they can turn a vehicle with reasonable behaviour into one that is uncontrollable.

In reference 26, AGARD Working Group 17 examined the current state of the art in considerable detail and it is not intended to re-examine that work here. The reference does provide an excellent overview of the situation as it applies to highly augmented, unstable aircraft, including some background to the criteria in use.

**2.4.4.3 Large Perturbation Response, Gross Manoeuvres and High Angle of Attack**

Airframe agility relates to the ability to perform large amplitude manoeuvres with precision and poise. Frequently, this can involve the vehicle transitting a degree of aerodynamic non-linearity, especially if high angles of attack become involved. Application of advanced technologies in aerodynamics, controls, control system design and propulsion have made possible extensions of the regime for controlled flight.

Design criteria which can deal with this situation are still being developed, but reference 26 does identify the scope of the requirements and criteria, identifying three basic aspects which are relevant as regards overall control margin requirements, viz:-

* Safety related tasks have to be fulfilled by highly reliable control effectors and tasks have to be prioritised such that the basic needs of stabilisation are fulfilled first. Remaining capability can be used to enhance airframe agility.
* Actuator rate saturation must be avoided. This is accompanied by large increases in phase lag which can reduce stability margins, or even make a vehicle unstable.
* Limitations due to hinge moment or other loads aspects must be considered.

Reference 25 does give a qualitative criterion in this respect but results in an increased number of independent control margin requirements to be satisfied. In reference 24, atttempts have been made to invert these requirements back into aerodynamic guidelines for use at the early project stage of development, before an FCS has been outlined. The key to successful design is to ensure that there are procedures to follow which will enable evaluation and demonstration of the airframe agility in safety. For example, the process would involve:-

* Establish an aerodynamic data base, capable of modelling any non-linear effects.
* Design an FCS, initially using linear methods. The use of bifurcation methods may assist in extending this to a non-linear capability by identifying where and what the likely changes in behaviour would be. Reference 36 shows such an application.
* Define a range of control inputs to exercise the system and then assess the response characteristics that result against the chosen design guidelines. It is important to look for effects such as saturation, rate limiting, response shaping, sluggishness, hesitation and the possibility of coupling the attitude response to the stick input over a range of frequencies.
* Account for any levels of uncertainty in any of the design parameters
* Make extensive use of piloted simulation and look for problems as well as establishing what you can do without finding difficulties.

Experience has shown that if this process unearths any phenomena that is not understood, then time must be taken to find out what is happening and understand the cause. References 28 and 29 indicate what might happen if such understanding is not available. Assessment of the robustness of the design will result in an FCS which provides the best possible airframe agility for a particular configuration. Design for "carefree" systems has to be particularly exhaustive in this respect. Figure 2.4.14, taken from reference 26, provides an example of one of the assessment techniques which may be used, looking at the effects of time delays on gain and phase margins.

Figure 2.4.15 illustrates a further assessment technique, which complements the linear derivative analysis methods. In this case, the migration of the roots of the characteristic equations is plotted to illustrate the effects of angle of attack. This method has the advantage of allowing the flight control system and aerodynamic damping effects to be included. Only the roots which influence low frequencies have been plotted.

**Figure 2.4.14: Effect of Overall Time Delay on Gain and Phase Margin**

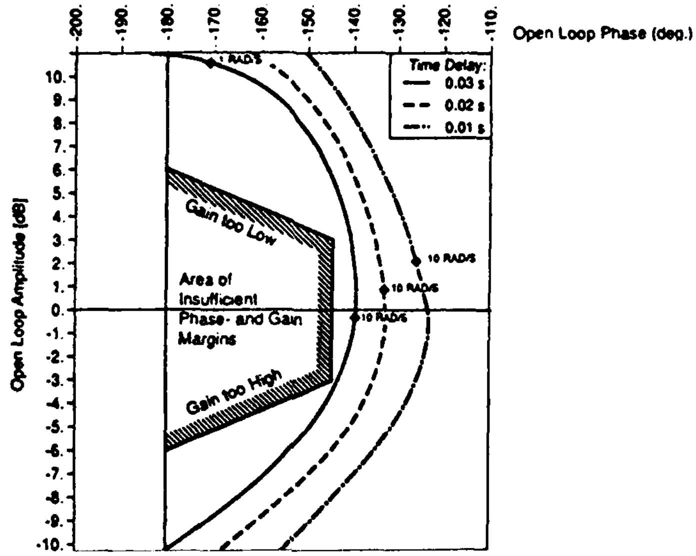
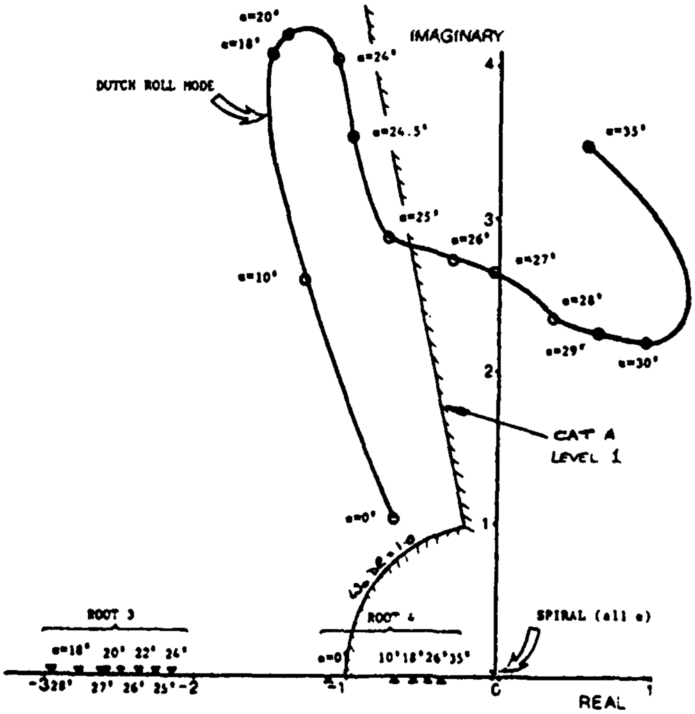



**Figure 2.4.15: Typical Migration of the Roots of the Lateral Characteristic Equation with Increasing Angle of Attack**



**2.4.5 Powerplant Integration**

The powerplant is a major contributor to the airframe agility, which so far has not been addressed other than where it affects the airframe configuration. In addition to providing the propulsive forces it is a major contributor to lift, especially for rotorcraft and V/STOL designs.

There are a number of issues which relate to airframe agility which should be considered in the design process, including the powerplant cycle and the way the powerplant is to be integrated onto the airframe.

The issues to be considered are:-

* Engine/inlet compatibility
* Engine power and power off-take
* Engine transient response
* Thrust vectoring

**2.4.5.1 Engine/Inlet Compatibility**

One of the objectives of the early configuration work is to select the intake type and position and ensure the shape of the ducts are such as to provide the necessary quality of airflow to the engine throughout the required flight envelope. Airflow quality is usually measured in terms such as swirl, distortion or pressure recovery. The main issue for modern combat aircraft is the size of the flight envelope which must be covered and the range of massflows which high power/thrust engines can experience. Signature requirements for the forward hemisphere can provide a very difficult engineering compromise, as such needs tend to mitigate against good aerodynamic design.

**2.4.5.2 Engine Power & Power Off-Take**

To examine the effects of engine power and power off-take, fixed and rotary wing vehicles need to be considerer separately.

For fixed wing aircraft, power and thrust are synonymous and thrust is a major driver for airframe agility, via the effect on performance and sustained turn capabilities. Thrust vectoring is excluded from these comments and is dealt with later.

Power off-take plays a secondary role. It provides the capacity to drive the aircraft systems, the hydraulics, etc. For high levels of airframe agility, it is essential that sufficient power can be made available for the actuation systems under all of the vigorous manoeuvre conditions, otherwise the FCS may be subject to rate saturation effects, with consequent control problems. This requirement can relate to handling qualities and is important for design of PIO free behaviour, particularly at low power settings, such as may occur during approaches.

Equally, it is essential that the power off-take demand do not cause the engine to stall, with the consequent problems which may follow, such as the need to shut down and relight.

**2.4.5.3 Engine Transient Response**

There are two areas which should be considered with regard to engine transient response, the fine control tasks, such as formation keeping and flight refuelling, and the gross manoeuvre aspects associated with "carefree handling" of combat aircraft.

Attention is turning increasingly to the engine response and its effects on aircraft handling qualities, primarily resulting from the response rates and characteristics of multi-spool, high by-pass ratio turbo-fan engines, which often provide good fuel efficiency, but can be slow to spool up in response to throttle demands compared to turbojet engines. This has been the subject of a recent NASA/Calspan study, reported in reference 37, which provides guidelines in terms of Handling Qualities criteria, from Level 1 to Level 3 handling, for use in the design and

assessment of engine response and its influence on the aircraft, particularly in high gain, closed loop, small perturbation tracking type tasks, such as close formation keeping.

The other aspect realtes to the large perturbation or gross handling of the aircraft in essentially open loop manoeuvring. When presented with a well designed "carefree" FCS, the pilot can expect to be able to attain maximum g or angle of attack in around one second. Ideally, he would like the same response from the engine.

Conventionally, engine response has been related to aircraft acceleration times and slow spool up times have been accepted in this context. However, in manoeuvring flight, pilots are controlling thrust and drag and trading kinetic and potential energy. Slow engine response has made this task very demanding, often requiring considerable anticipation from the pilot, particularly for aircraft with turbofan engines.

When making a throttle movement, the first concern of the pilot is " Will it work?" It is still possible that the engine might stagnate or stall, although electronic controls and good inlet compatibility will reduce the likelihood of these events. From the time of initiating the throttle movement until the engine stabilises at the required level, the pilot's attention may be distracted from the task in hand, by the need to monitor system status. With modern engines, that time seems to have increased by an order.

Combat pilots must anticipate their actions by seberal seconds in order to have the right power setting. This might be acceptable for airshows, but can provide an unwelcome distraction in the thick of combat. Flying aircraft with such characteristics places an increased burden on the pilot training programmes.

At present, no guidelines can be offered as to what design aims or criteria should be used or are possible. This is one area which would benefit from research in depth. Spooling times for the engine are dictated by Newtonian physics, so another way of controlling thrust is probably required to produce the sort of response which would match the airframe's capability. Thrust spoiling, as demonstrated on the F-15 SMTD aircraft may be a way forward, see references 30 and 31.

#### 2.4.5.4 Thrust Vectoring

Thrust vectoring has been the key enabling technology for the rotorcraft world. However, for fixed wing applications, it has until comparatively recently, been more of a curiosity. Initially, thrust vectoring was implemented for the vertical take-off and landing capability and this remains the only fixed wing application that has seen service use, to date, ie the Harrier/AV-8 in the West and the Yakolev 38 in the East. Reference 32 examines the design and performance assessment of such vehicles in some detail.

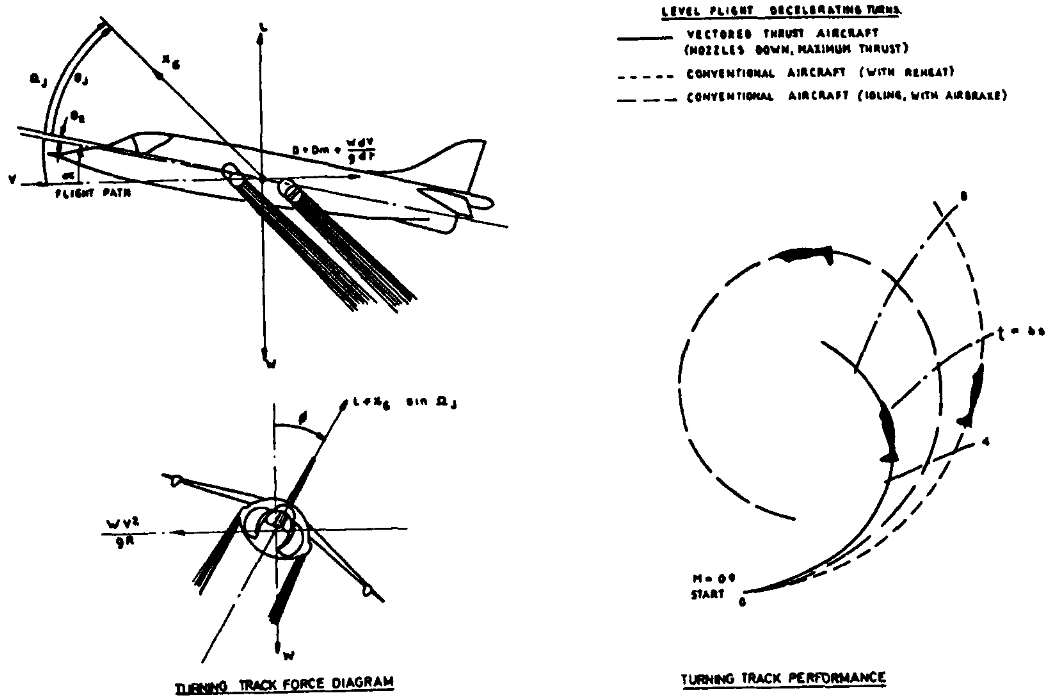
As part of the AV-8 programme, an investigation of the use of vectored thrust in forward flight (VIFF) was undertaken. This was found to provide rapid deceleration capability whilst increasing lift, such that turn radius could be significantly reduced. As such, the manoeuvre could perhaps be regarded as a forerunner of PST. In this particular series of configurations, the VTOL capability has produced an enhanced airframe agility.

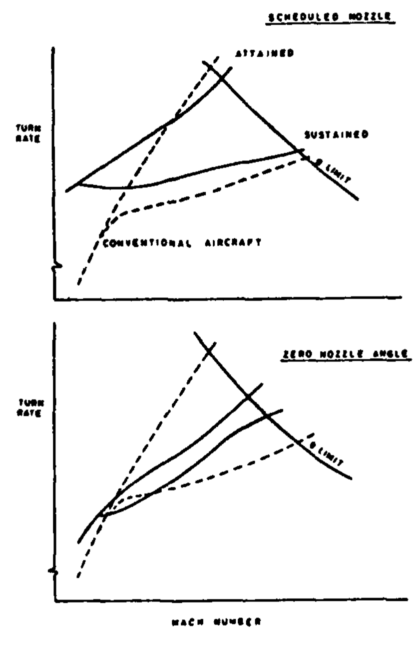
Until recent times, thrust vectoring was associated with a significant mass penalty which has tended to preclude its more general use. However, advances in engine and nozzle technologies are changing this situation rapidly, with reducing penalties realiseable. Now the use of thrust vectoring as an additional and powerful control, both in pitch and yaw, has been shown to be possible without compromising air vehicle performance over the full flight envelope. For such configurations, the main use is to enhance controllability at very low speeds, or at angles of attack where conventional aerodynamic controls are reducing in their effectiveness. Quickness of response is the goal for these cases.

Precision of control under these flight conditions enhances airframe agility and a number of the metrics proposed in section 2.3.3 may be used to assess the effects. Additionally, a number of varied flight experiments have been performed, including the F-15 SMTD, X-31A and F-18 HARV, whilst a further technology demonstration has been completed by the YF-22 aircraft.

In these applications, thrust vectoring has been used to enhance pitch (and yaw) control at high AoA, enabling the vehicles to achieve significantly increased roll performance, especially around maximum lift. This is demonstrated in figures 2.4.16 and 2.4.17 taken from references 33 and 34, where pitch vectoring only has been used. Yaw vectoring would allow co-ordination of rolling to even higher AoA, by enabling the vehicle to roll about its velocity

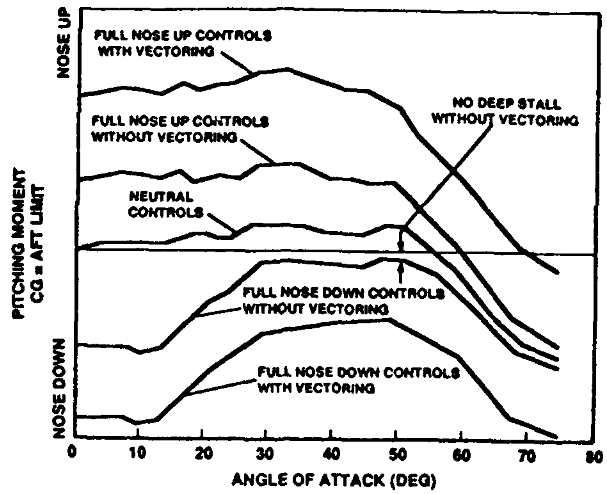
**Figure 2.4.16: Effects of Thrust Vectoring on Combat Turn Capability**



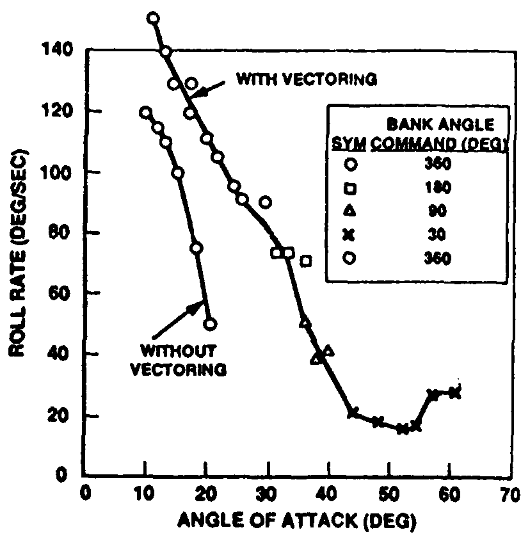




COMBAT CHARACTERISTICS
THRUST VECTORING VERSUS CONVENTIONAL AIRCRAFT

**Figure 2.4.17: Benefits on High Angle of Attack Manoeuvre Capability due to Thrust Vectoring**




*Pitching Moment Comparison*




*Roll Rate Comparison*

vector without excessive sideslip. Indeed, the benefits of yaw vectoring may be even more significant for agility than pitch vectoring.

To obtain the best use of thrust vectoring, its use should be transparent to the pilot. To achieve this requires the propulsion system control to be integrated with the flight control sytem. This has implications for the actuation systems, control rates and phase lags, which must meet the same requirements for the propulsion components as the primary actuation aerodynamic controls. Failure to achieve this could leave the way open for non-linear effects to intrude into the handling, reducing control effectiveness, giving handling peculiarities, or, at worst, causing PIO and loss of control.

One issue that remains for such systems, is the relation between control response and power response. Delay in achieving the necessary power levels may force an unwanted compromise between available control and necessary control, especially if dynamic manoeuvres were to be started from comparatively low power levels.

### 2.4.6 Concluding Remarks

Clearly, the basic levels of airframe agility are set by the initial design of the configuration, with sizing dictating the steady state performance and manoeuvre capabilities. The classical parameters of Specific Excess Power, Sustained and Attained Turn Rates are still the fundamental starting points for agile design. Handling qualities and carefree manoeuvring capabilities which highly augmented flight control systems can offer allow the maximum of the basic capabilities to be extracted, however, poor design in these areas can limit the vehicle to less that its maximum capability.

The use of the proposed agility metrics can assist the designer in evaluation of the alternative solutions, but further work is still needed to determine which are the most appropriate. Indeed, that may be a function of the role that the vehicle has to perform at any time and could even vary during a mission, depending on the phase.

The concepts associated with mission task elements will be a major assistance in making such decisions.

The key messages are that:

* Airframe agility is designed in form the outset.
* Airframe agility cannot be added later, except in very unusual circumstances.
* Good, robust FCS design is a prerequisite, as is carefree handling.
* The FCS cannot make up for deficient basic design, although it will mask it to a point.

The Appendix A to this report provides an example of how airframe agility methodology can be applied in the case of a rotary wing aircraft. The Appendix discusses the considerations and trade studies which associated with the design of an agile air to air combat helicopter. It endeavours to illustrate that it is essential to consider more than just the airframe in this design.

## 2.4.7 References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## 2.5 Airframe Agility Evaluation

### 2.5.1 Introduction

This section shall discuss the evaluation of airframe agility. Historically it has been the evaluation community which has been faced with making sense of new aircraft capabilities and then providing feedback to designers. Several examples have been discussed by Skow in paper 1 that have demonstrated how deficient our current evaluation techniques are at characterizing the transient behavior of modern aircraft. It has been one of the aims of this working group to investigate agility evaluation methods. The previous sections in this chapter have emphasized the fact that design for agility requires a balance with other operationally significant characteristics. This has an important impact on the evaluation for agility as the process of evaluation must be iterative throughout development to ensure the correct balance. From this concept has stemmed the realization that the evaluation of agility should not be left to flight testing alone as the following discussion will prove, but implemented with a wide range of simulation, simulator, and flight test techniques. Unfortunately, a great deal still needs to be done regarding agility evaluation methods. The full potential of agility still requires a great deal of development as does the relation of agility with other design components. This can only be realistically managed if a sound evaluation approach is developed to which all researchers and operators can contribute.

The discussion shall start with the agility evaluation philosophy. Experience with simulations and flight tests at the time that this report was prepared will then be briefly summarized. Analyzing agility data will then be discussed emphasizing transient agility recognizing that very little design correlation exists for the experimental and operational agility metrics. Current proposals for specifying airframe agility within the context of existing flying qualities specifications will then be mentioned. Finally, the state-of-the-art in airframe agility evaluation will be summarized identifying the critical gaps in order to guide future efforts.

### 2.5.2 Evaluation Philosophy

The evaluation of operational agility has two aims: demonstration of specification compliance and measurement of data to present in the flight manuals and develop tactics. The working group believes that the classical "flight manual" per se, might be an outdated method for presenting aircraft information to the pilot. Newer and more novel approaches should be considered to effectively present the true capabilities of the aircraft. Modern computer display methods could aid in the presentation of transient characteristics. Evaluation techniques must be developed to suit the new data presentation formats.

A build-up approach is suggested which measures each individual characteristic followed by all in combination. The metric structure developed in Chapter 2 Section 2.2 is ideally suited to this approach. The build-up in airframe characteristics would be a precursor to the evaluation of the complete aircraft operational agility evaluation which is discussed in Chapter 5.

Technologies available today provide for a large array of tools for the evaluator to monitor the contribution of agility to the design balance. Four types of evaluations are conceivable:

1) analytical and design studies implemented with a non-real-time simulation,
2) real-time and pilot-in-the-loop simulator studies,
3) experimental flight tests
4) operational flight tests

Simulations and simulators are widely available for controlling and assessing most aspects of flight mechanics and air combat. A complete capability in these areas permits trade-offs in all the aircraft design attributes. Experimental flight tests are now only relied on for the "final demonstration" of a capability. The cost of flying all possible test conditions has become prohibitive putting more emphasis on simulations and simulators. Finally, the distinction between experimental and operational flight tests has become somewhat vague when evaluating agility as it is inherently operationally related.

The observations made by several international organizations currently conducting agility metric research and development will be discussed next. The observations have primarily been based on simulator studies but some flight test data are now available. The simulator studies have covered all the transient, experimental, and operational aspects of airframe agility. The limited flight testing have only covered the transient and experimental categories. Efforts under way now, such as the X-31A and NASA F-18 HARV, will provide more data in all the areas addressing many of the outstanding issues identified in this report.

### 2.5.3 Airframe Agility Simulation and Simulator Studies

#### 2.5.3.1 NASA

A comprehensive NASA simulator effort was conducted by Murphy, Bailey, and, Ostroff at the Langley Research Center. (2) A great many control design metrics (CDM) were identified from this study including numerous presentation schemes. Although emphasizing the controls engineer design problem, the applicability to the broad category of experimental metrics cannot be overstated.

The simulation was a high-performance single-place fighter-attack aircraft with a gross weight of 45,000 lbs. The aircraft possessed two turbofan engines capable of 16,000 lbs thrust at maximum afterburner. The simulation was implemented in the Langley Differential Maneuvering Simulator. This simulator possessed two identical cockpits that were housed in 40 ft diameter domes. Only one sphere was used for the study without any target aircraft. This simulation was intended to represent a typical current generation fighter aircraft. Apart from the extensive set of experimental metrics studied a number of lessons learned from the study are worth noting:(2)

1) "pilot-in-the-loop constraints represent real limits on the level of agility allowed and represent requirements that must be incorporated in the design"

2) control design metrics for advanced fixed wing aircraft can be grouped into axial, pitch, and roll axes.

3) "axial metrics highlight acceleration and deceleration capabilities under different flight loads and include specific excess power measurements to characterize energy-maneuverability".

4) "pitch metrics apply to both body-axis and wind-axis pitch rates and accelerations....included in body-axis pitch metrics are nose pointing metrics that highlight displacement capabilities between the nose and the velocity vector".

5) "roll metrics focus on rotational capability about the wind axis (only)".

As a result of this study the need to clarify the axes systems for the various agile motions is shown to be important. In many cases, body, wind, and inertial reference systems are used in combination. As a useable set of airframe agility metrics are finalized, this must be kept in mind.

In addition, NASA Langley Research Center is pursuing a broad control design method which blends the requirements of Control power, Robustness, Agility, and Flying Quality Tradeoffs (CRAFT). (3) This technique provides a graphical representation of control design metrics. This effort should result in clarifying the usefulness of many experimental metrics in the design process.

#### 2.5.3.2 Eidetics

Many simulator studies have been conducted at Eidetics primarily modelling combat engagements. These studies have provided valuable insights into the transient, experimental, and operational airframe metrics. With the identification by Skow of the time line approach, the global goal of agile motions were clarified. (1)
Eidetics researchers used the Air-to-Air System Performance Effectiveness Model (AASPEM) simulation to identify the tactical utility of agility. The primary lessons learned from the continuing Eidetics research are:

1) agility must be balanced with other combat attributes making its characterization through metrics important to effectively implement a balance.

2) "potential for enhanced agility to increase the combat effectiveness...has been equated to increases in conventional E-M performance".

3) ranked order of priority of agility characteristics were: torsional, pitch,and axial agility.

2.5.3.3 University of Kansas

Numerous proposed agility metrics have been assessed through simulation at the University of Kansas. (4) This effort was primarily driven by the NASA F-18 HARV program. The study entailed use of a F-18 simulation implemented with the NASA SIM 2. The F-18 was modelled with a non-real time, high fidelity, six degree of freedom, non-linear simulation using F-18 aerodynamic, engine, and flight control models that was adapted to run on an Apollo work station. The model was used initially to study various proposed metrics in an open-loop fashion using trial and error to determine control inputs. Other important issues that were to be studied included pilot cues for agility maneuvers and data analysis and reduction routines. Important lessons learned were:

1) power onset parameter, power loss parameter, nose up pitch rate, nose down pitch rate,and the time to roll through 90 degrees form a simple set of agility metrics.

2) links between agility and aircraft configuration design should be explored.

3) pilot rating scales for agility are needed to determine the relationship between good flying qualities and agility.

2.5.3.4 McDonnell Aircraft Company

Investigation of the significance of various metrics has been conducted at McDonnell Aircraft Company by Riley and Drajeske. (5) Simulation was used to conduct the ongoing investigations. An F-15C cockpit and stick in a fixed-base simulator was used along with the Generic Aircraft Linear Simulation Program (GENAIR) to specify the aircraft dynamics. Experimental and operational metrics were investigated using multiple pilots. Significant lessons learned for the torsional agility study revealed that:

1) "nonlinear increase in exchange ratio exists with increasing torsional agility".

2) "increased torsional agility in 1 vs 1 engagements did not significantly affect the time to defeat and opponent".

3) "a practical upper limit on roll dynamics was found beyond which increased maneuverability decreased agility".

4) "as the agility of a threat increased it became increasingly more difficult to defeat an opponent through airframe agility alone".

2.5.3.5 UK Defence Research Agency

In the late 1970's, the UK's Defence Research Agency (formerly Royal Aerospace Establishment) embarked on a research program to identify the performance and handling attributes that affect helicopter agility. The work encompassed theoretical studies and a series of flight and piloted simulation trials to quantify agility. The latter were conducted within a TTCP (HTP6) collaboration and included joint experiments with NASA/US Army. The Bedford flight simulator and NASA's Flight Simulator for Advanced Aircraft (FSAA) were both configured with generic battlefield helicopter models (Helisim and Armcop respectively) and a collection of nap-of-the-earth tasks created on

miniature landscapes. The results of this activity demonstrated a strong sensitivity of agility to key handling characteristics and the potential for dramatic improvements through task tailored stability and control augmentation. (6,7) The research also demonstrated the power of simulation in conceptual and trade off studies. Concurrent flight trials confirmed many of the simulation findings, but also highlighted some shortcomings in ground-based simulation and the potential dangers of extrapolating results to high agility where the fidelity of the simulated visual and motion cue environment became degraded. The flight trials included the first ever air-combat experiments and low level tasks flown over marked out 'racetracks' on the Bedford airfield. The sensitivity of pilot opinion and associated handling qualities ratings (HQRs) to the desired and adequate task performance levels was also identified. In particular, these experiments demonstrated the need for special handling qualities at the edges of the usable flight envelope, facilitating what was later to be described as carefree handling. Key activities at the DRA during this period were,

1) Development of mission task elements for helicopter military roles for use in simulation and flight test (Ref 1, 2, 3, 4, 6, 10, 15, 16)

2) Development of the Conceptual (Helicopter) Simulation Model (CSM) to define the target flying qualities for future types (Ref 7).

3) Development of novel flying qualities response types for meeting specific task requirements, particularly the flight path control system that elicited favorable pilot reaction and startling improvements in task performance (Ref 7).

4) The agility factor was derived as a measure of usable performance in a mission task element, hence quantifying the potential gains from improved flying qualities (Refs 3, 4, 5, 6, 9, 12).

5) The development of Inverse Simulation for comparing the performance attributes of different control/airframe design characteristics (Ref 8).

At the time the DRA program was initiated, typical rotor craft 'agility' requirements were based on specific point performance criteria, for example speed, acceleration, rate of turn characteristics etc. The extent to which such criteria translated into achievable levels of agility for actual battlefield type manoeuvre, in low level stealthy NOE flight, or up and away air combat type maneuvering, was open to question. Furthermore, little work had been done to establish a means of measuring and quantifying the levels of agility needed for such cases. Handling qualities requirements were to a large extent of a qualitative nature, whereby the onus was placed on the designer to determine and evaluate the appropriate handling qualities characteristics. It was clear that such quantitative criteria as then existed had not served to guarantee that desirable handling and agility characteristics would be achievable.

The simulation of helicopter agility and flying qualities using ground - based facilities has long presented a technical challenge in terms of the required fidelity of the task cue environment. As air-vehicle/mission attributes, flying qualities are especially task-sensitive and the fidelity of visual and motion cueing needs continuous assessment and validation for new applications. While many studies, spanning more than 20 years, have produced useful results and general guidelines, it is a relatively recent acquisition initiative to require demonstration of flying qualities compliance in simulation prior to flight. There are, however, no definitive fidelity standards or validation criteria for helicopter research and development simulators with respect to their use in this context. What is becoming clear is that the standards required are likely be very high for some critical flying qualities, beyond that currently available from simulation technology. During the development of ADS33C, for example, data from research simulators were used to support the development of criteria boundaries. One of the most demanding handling criterion relates to the (frequency) response bandwidth between the pilot's control input and aircraft's attitude response. A conclusion from the ADS33 development work was, "there were too many unresolved questions about data from rate response types obtained from simulation to use them in a specification development effort", and that "only flight test data can be reliably used to define bandwidth boundaries". Problems stemmed from visual scene generation transport delays, lack of scene texture and anomalies in motion/visual cueing, particularly intrusive during nap-of-the-earth mission task elements. These problems were encountered on the world's most advanced flight simulator at that time, the NASA Ames Vertical Motion Simulator (VMS), suggesting that less capable facilities would have an even smaller usable

envelope of realistic fidelity.

Simulation technology has advanced considerably over the five years since the first publication of ADS33. The VMS has been upgraded to improve many of the deficiencies identified in the ADS33 database development. VMS simulations of nap-of-the-earth manoeuvre conducted in 1989 produced pilot handling qualities ratings up to 1.5 points worse than in flight. Degraded visual cueing in the simulator was a source of many of the adverse pilot comments, particularly relating to field of view, scene resolution and depth perception.

Defining tasks for pilots to judge flying qualities is a critically important activity, full of pitfalls. How should the task performance levels be set to delineate Level 1, 2 and 3 flying qualities? How should the task cues be presented to the pilot? How far should 'clinical' tasks be augmented with unnatural features to compensate for degraded visual cues? The resolution of these questions raises problems, not only in simulation, but also in flight trials, where the test environment is often artificially created on an airfield to enable tracking measurements to be made. A common goal of all flight and simulation activities in this area has to be the determination of the impact of different flying qualities on mission effectiveness. A major issue then becomes the degree of similarity between the real 'operational' world and simulated flight tasks.

During the last 24 months, DRA has begun operations with the Large Motion System (LMS) element of the Advanced Flight Simulator (AFS) complex. This new facility offers the potential to expand the range of configurations and tasks that can be simulated with high fidelity. The need to support a range of helicopter research activities led to a concentration on helicopter simulation during the first year of operations. Tasks needed to be developed on the computer-generated-image (CGI) database and an initial set of motion drive laws appropriate to tactical flying in the low to mid speed range prepared. A particular trial series supported the EuroACT helicopter collaborative program with the goal of defining flying qualities standards achievable by the current maturity level of Active Control Technology (ACT).(8) The principal findings of the research are as follows:

1) Level 1 handling qualities were achieved for roll/pitch rate response types, at moderate levels of aggression, on the AFS; these results, and the bandwidth values for the Level 1/2 boundaries are consistent with the ADS33C criteria set by flight data gathered on fly-by-wire helicopters.

2) the variation of handling qualities with attack factor has been reproduced on the AFS, although there is evidence that, at high agility factors, simulator visual/motion cues need improvement.(9)

2.5.3.6 MBB

Major contributions to transient agility research have been provided by Dr Herbst and his group at MBB. (10) Looking at agility as primarily a flight path related characteristic, they felt that there was a need to combine the benefits of three basic approaches:

1) differential geometry derivations along the flight path,
2) equilibrium considerations of aerodynamic and inertial forces acting on the aircraft trajectory, and
3) flight control approaches where agility is considered to be a function of stick and throttle movements (as compared to "maneuverability" which is related to control positions).

As a result of simulations, three major components of agility have been identified: longitudinal agility which is the change in tangential acceleration; turn or curvature agility which represents changes in centrifugal accelerations acting perpendicular to the flight path; and torsion agility which represents the capability of the aircraft of twisting its maneuver plane. Following Dr Herbst's recommendation, it is mandatory in order to measure the potential of agility of an aircraft to define a set of standardized maneuvers related strongly to each of the three types of agility as defined by Dr Herbst.

For longitudinal agility a straight and level 1g acceleration/deceleration maneuver should be performed with typical throttle and speed brake step inputs. These would be performed at specific pressure altitudes which permit the measurement of the increase and decrease of the flight path acceleration/deceleration.

The curvature agility will be represented best by performing maximum performance abrupt wind up turns starting at a given airspeed/Mach/pressure altitude in a straight and level 1g condition or from established level turn conditions at elevated load factors (preferably at maximum sustained rate of turn). Data analysis will look for the maximum rates of the load factor increase that are achieved.

Torsional agility will be measured from loaded roll maneuvers performed at either maximum instantaneous level rate of turn for a given Mach/pressure altitude or at the maximum sustained level rate of turn performance for a certain Mach/pressure altitude. Data analysis will concentrate on the loaded roll rates and roll accelerations.

### 2.5.4 Airframe Agility Experimental Flight Tests

#### 2.5.4.1 AFFTC

As already emphasized in section 2.2, a three-year flight test program was implemented at the AFFTC to study proposed agility metrics using fixed wing fighter type aircraft. (11) The test program used flight testing of the X-29A, F-16, F-18, F-15, A-37, and RF-4. These aircraft types represented a very wide array of fighter aircraft technologies and capabilities. Related experience was presented in References 18, 21, 22, 23, and 24. The techniques investigated focused on obtaining data on experimental metrics.

The complete set of test techniques were comprised of: Load Factor Capture; Loaded Roll; Loaded Roll Reversal; Pitch Angle Capture; Level Turn; Angular Reserve; Yaw Pointing; High AOA Capture; High AOA Roll; and High AOA Roll Reversal. These techniques and the results obtained are described in detail in Reference 11. Practical methodology and concerns were summarized by Lawless (24) for the pitch capture and loaded roll flight test techniques.

Testing was conducted at 20,000 ft and at 200, 350, and 580 knots for most of the aircraft evaluated. These conditions covered the below corner velocity, near corner velocity, and above corner velocity conditions for typical fighter type aircraft. For future agility studies, these conditions should be used as a starting point since real flight test data now exists. The test matrix was developed with the metrics categorized by axis(pitch/roll/yaw) and maneuver (flight path/nose pointing).

Since the test techniques were all closed-loop the capture tolerances required a great deal of refinement. Typically, too tight tolerances resulted in overshoots, and loose tolerances were found to not be operationally realistic. In the future, the tolerances will have to be selected by the metric user with this fact in mind. Lawless found that rehearsals in simulator could increase test efficiency by practicing the setups for each technique but unfortunately were limited in fidelity, motion cues, and displays. In conjunction with the simulator then, Lawless discovered that airborne practice with real-time feedback from a control room was beneficial.

Cockpit displays also hindered performing some of the techniques. For pitch pointing, high pitch rates made HUDs difficult to read so ADIs were used. For rolling maneuvers digital load factor displayed on HUD prevented precise load factor tracking so pilots preferred learning a stick input for a desired motion in the simulator permitting concentration on the capture when actually flight testing.

Techniques also differed between AOA limiter equipped aircraft and non-limiter equipped aircraft. Consequently poor flying qualities could hinder performing some of the techniques, eg the F-4 at moderate AOA has very bad flying qualities.

Finally, aircraft comparisons cannot be made if any of the aircraft are restricted to artificial limits, eg load factor limits tended to dominate pitch pointing results.

Within reference 11, Lawless eliminated a number of the proposed transient parameters because they did not add any new information, specifically:

1. similarity between Nz-dot , curvature agility, and turn rate-dot over the range of $\alpha$ and $\beta$ tested. Nz-dot was selected to continue the investigation because it was familiar to pilots and designers;

2. similarity between pitch and $\alpha$ acceleration results. Pitch acceleration was chosen because it was easily derived from the available instrumentation;

3. no difference between rolling parameters measured in the body, flight path, or aerodynamic axis system were observed for $\alpha < 36$ degrees. Maximum instantaneous roll acceleration (p-dot) was therefore selected for analysis, again for familiarity;

4. the torsional (rolling) agility parameter was not used because it was extremely sensitive to the instrumentation output and was therefore rendered unusable;

One effort scheduled to begin shortly involves the F-16 Multi-Axis Thrust Vectoring (MATV) demonstrator. This program includes a "functional agility" evaluation phase that is expected to provide valuable information about the benefits of a multi-axis nozzle that can be compared with two dimensional nozzles.

Another effort implemented the Standard Evaluation Maneuver Set for agility briefly discussed in reference 20. Flight tests were conducted by the United States Air Force and Navy. The results of this effort has not yet been discussed in open literature. This effort is expected to bring to light more operational agility data.

2.5.4.2 DRA Helicopter Flight Test

Flight research at the Defence Research Agency has also been focussed on agility; this included an exploratory investigation of a 90 degrees transient turn manoeuvre in low level flight using an instrumented research Puma helicopter and an Army Lynx during the early 1980s.(12) The manoeuvre was chosen because it represented a basic element of the low level transition and nap-of-earth flight phases of a typical battlefield mission profile. The test objective was to evaluate turn efficiency, over a range of speeds, through the task time and agility kinematic based metrics centered on the speed and track over the ground. The test manoeuvre was essentially a coordinated turn, flown to achieve a 90 degrees change in heading as quickly as possible, while holding height and speed sensibly constant.

The concepts of an 'effective radius of turn' (Re) and a 'turn agility factor' (Af) were introduced, which were intended as generic measures that would serve to: supplement requirements for maximum turn rate; provide a relative measure of the turn performance of different types; and determine the maximum speed at which a given terrain could be overflown. The generic measures were determined as follows:

1) Re - a measured average radius of turn at a given speed,

2) Rn - ideal turn radius calculated using the mean airspeed and maximum angle of bank achieved,

2) Af was calculated as the ratio of a notional ideal turn radius Rn to the actual measured Re.

Hence, the Af represents a index of the useable turn performance relative to the maximum theoretically available turn performance, net of all manoeuvre transients and aerodynamic effects; the Af would be expected to rise to unity should the transients be zero.

The main findings were as follows:

1) task times were almost constant at 5 sec and 6 sec for Lynx and Puma respectively over the test speed range (40-100kn).

2) Af values for the Puma lie within the range 0.5 to 0.6; the improved task times for the Lynx indicate higher achievable Af's, up to 0.7.

3) an automatic height-hold flight control system function will be essential for improved height control in NOE flying.

4) some form of manoeuvre limiting function will also be required to allow the pilot to exploit the full potential performance with safety.

A second flight activity at DRA during the 1980s was aimed at establishing the control and handling requirements for precise flight path manoeuvering at high bank angles close to the ground. (13,14) A special 'circles' MTE was marked out on the airfields at Bedford and Manching (DLR's test centre) and flight trials with Puma and Bo105 carried out. The data revealed the following findings;

1) the bare airframes were essentially poor Level 2/ Level 3 for this task.

2) frequency spectra of pilot control activity provides a direct measure of pilot workload for this kind of task; there was strong evidence of considerable pilot control remnant, ie activity uncorrelated with any task errors and essentially an accumulation of pilot errors of judgement and wasted energy.

3) the effects of wind direction and strength on pilot workload and task performance are considerable; an increase of wind strength from 5 to 15 knots can degrade handling qualities by 2->3 points.

4) active control systems offer considerable scope for improvement with this kind of flying.

A third flight program at the DRA was undertaken to quantify the agility levels of current operational types in flight tests flown with the performance margins expected of future projects. (9,15) The agility factor concept was developed from that described in Reference 12 and applied to measure the ratio of performance used relative to some defined and (theoretically) achievable standard. The principal low speed re-positioning MTEs flown were the lateral sidestep and longitudinal quick hop. The key results were as follows;

1) agility factors of 0.4->0.6 were achieved with the Puma, 0.5 -> 0.7 with the Lynx. At maximum values, handling qualities ratings in the poor level 2/ level 3 range were returned.

2) the performance standards of the Lynx in terms of primary roll and pitch attitude response characteristics and engine/governor/thrust response characteristics were deemed to be good standards for future types.

3) the research findings highlighted the critical effects that levels of pilot aggression or task urgency have on handling qualities.

4) the research confirmed the importance of conferring carefree handling capabilities on future types to ensure that handling deficiencies do not spoil the exploitation of high performance.

Elsewhere, in the USA, Canada and in Germany, similar research activities were taking place. In the US, the main focus of the work was to update their handling qualities requirements for military rotor craft. Canadian and European Government research laboratories were invited to participate in this program to ensure that the best available data and facilities were available to the upgrade work. Stemming from this, in 1985 a first draft set of proposals for radically new handling qualities criteria and test and analysis procedures were published; these proposals were later to be adopted as ADS33C - the flying qualities requirements for the US Army's LH Comanche helicopter. (16) Before the new criteria could be fully developed and adopted, validation work was needed. A significant proportion of the associated collaborative research was conducted under the auspices of a TTCP(HTP6) collaboration involving US Army, NASA, the DRA and IAR (Canada), to review proposals for the update of the US Mil-H8501A. The DLR Braunschweig were also involved through joint experiments under the auspices of an MoU agreement with the US, and through an informal collaboration with the DRA.

2.5.4.3 Boeing/Sikorsky

Sikorsky has conducted important flight test work on agility and maneuverability using their Fantail Demonstrator. (17) Spurred by research and development to support the Comanche helicopter, the Fantail flight testing sought to explore the impact on agility which the design provided. The demonstrator was a modified S-76B prototype aircraft with a new tail fan system for antitorque purposes. Perhaps the most significant agility maneuvers investigated were rapid yaw turns in both hover and forward flight conditions. Other maneuvers that were enhanced by the technology were the roll, split-S, and hammerhead. In addition to this specific work, Sikorsky used extensive simulation and simulators to tradeoff maneuverability and agility metrics.

2.5.4.4 X-31A

So far, no dedicated agility testing has been reported among the X-31A flight test activities. Most of the testing concentrated on achieving a high angle-of-attack/post-stall (PST) flight envelope. The pilot is able to perform full stick deflection 1g and loaded PST entries and velocity vector rolls while remaining departure free up to a maximum of 70 degrees angle-of-attack and 0.7M at a minimum altitude of 10,000 ft PA.

Included in this testing were limited sustained turn performance tests with military thrust and maximum after-burner at 10,000, 20,000, and 30,000 ft PA and a number of 1g level accelerations and decelerations.

From the aircraft response data obtained from numerous stick inputs and test maneuvers like rapid rolls and loaded rolls, pull-ups, push-overs, etc a limited amount of dedicated agility evaluations could have been achieved. As of now, it is not known if such data have been released or will be made available to agility researchers. This working group feels that perhaps the most important contribution that the X-31A effort can provide is in the area of the potential benefits of the airframe to operational agility metric development and database construction.

2.5.4.5 NASA F-18 HARV

As for the X-31A, the flight testing of the NASA F-18 HARV has focused on the development of the thrust vectoring system. It is not known what agility data has or is planned to be measured with this research vehicle.

## 2.5.5 Agility Data Analysis

Agility data analysis is receiving a great deal of attention now that numerous metrics have been proposed. This effort has focused on the response of the aircraft to pilot inputs in the time domain. Like flying qualities data reduction, the agility data are extracted from the time history of the flight test maneuver. Current data extraction techniques will be presented.

2.5.5.1 Application of the Agility Metric Structure

To illustrate how the transient, experimental, and operational metrics are applied, a hypothetical missile engagement sequence for a fighter aircraft will be used as an example. For this situation it is assumed that the friendly aircraft is cruising at 450 knots at 20,000 ft when it must engage one adversary aircraft and recover to be ready to engage another adversary. To employ its missile, the friendly aircraft must make a nose pointing transition of $\Delta\theta$ and $\Delta\psi$. This engagement could be performed with a maneuver sequence such as: roll-in, load, turn (mainly horizontal), missile launch, unload, roll-out, and acceleration back to cruise conditions. The time-line for the sequence was illustrated in Figure 2.2.12.

The metric hierarchy facilitates a top-down analysis approach. The most important global agility metric is the time to complete the missile engagement. The more agile the friendly aircraft, the quicker this task can be completed. A designer may look to reduce the engagement time so as to be more operationally effective by being able to engage more aircraft. The maneuver sequence provides a basis on which to break the missile engagement task into mission task elements (operational metrics). At this level, the designer can identify which mission task element(s) is/are the reason for the excessive time delays if the time taken is noticeable long. Metrics such as the CCT and DT parameter

will provide guidance for comparison to tactical knowledge of the response and launch times of various threats. The designer can then identify which maneuvers take too long or must be shortened. The horizontal turn $\Delta\psi$ which takes longer for a current generation fighter as the flight path is bent slower could be improved with technologies than permit rapid nose pointing. The experimental metrics then provide information necessary to measure the transient turning characteristics and determine if it has been reduced. Throughout the sequence transient metrics identify when the peak state change events occur. To apply the metrics for design and specification, a method is required to focus on specific quantitative events. This procedure occurs at the lowest level of detail, the transient metric level. At this level, the instantaneous response of the aircraft can be analyzed. The AFFTC has suggested onset and capture transient analysis as a means of accomplishing this.

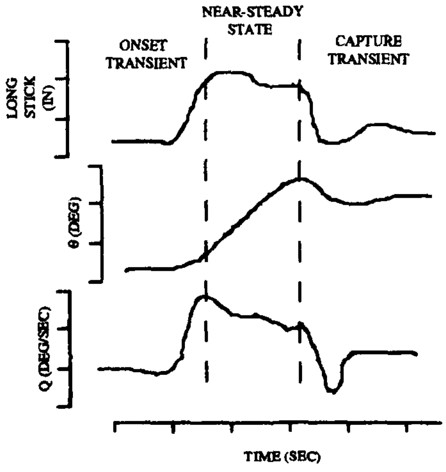
### 2.5.5.2 AFFTC Onset and Capture Transient Analysis

Lawless, described a process through which agility could be linked to design criteria. (11) The process identified a number of parameters, Agility Design Parameters (ADP) and analyzed the time history during the test maneuvers. The approach was referred to as onset and capture transient analysis. The onset and capture transient analysis is based on data gathered during closed-loop flight tests such as capture tests. Lawless defined three time intervals with which to classify information for data base building. These intervals were:

1) T1 - interval between control input and achieving a steady-state
or near steady-state condition;
2) T2 - steady-state or near steady-state condition;
3) T3 - interval between capture control input and when flight conditions
fall within capture criteria.

Reference 11 provides an example maneuver segment illustrated in Figure 2.5.1 for a pitch angle capture. From these segments, Lawless suggested that classical performance and flying qualities may be linked and the data can be tabulated to model the response of the aircraft. Segment T1 provides data for the onset characteristics, T2 provides a means to extrapolate or interpolate results, and segment T3 provides the data for capture transient analysis. Lawless remarked that T2 is the most repeatable of the three segments and therefore presented the best means for developing a mathematical model. Lawless established a database for modelling onset transients and functional agility but capture analysis was left to future effort. The suggested benefit of this effort is that the functional agility of an aircraft could potentially be predicted without the need for extensive flight testing.

Figure 2.5.1 AFFTC Onset and Capture Transient Analysis Example
(pitch angle). (11)



Onset Phase . During data reduction of the extensive set of data gathered at the AFFTC agility metric development effort, a new method was described for characterizing the onset phase of a response referred to as the rise time acceleration parameter. Butts and Lawless noted that the established parameters for steady state phase (maximum rates, maximum accelerations, time constants) were not suitable for the onset phase. (18) The onset segment contains the main transient data - most notably jerk characteristics and quickness characteristics from the agility definition. In this segment, the state change is commanded and the quickness of the motion.

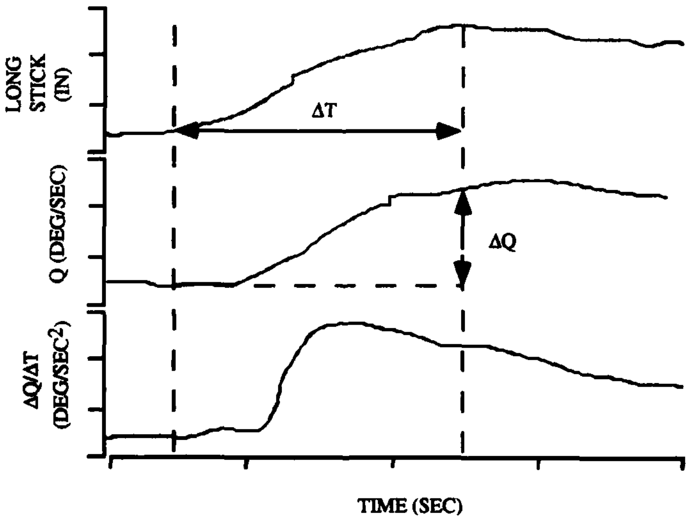
Steady State Phase. The steady state segment begins when a steady-state condition of predictable motion is achieved. Lawless points out that the T2 segment represents that part of a maneuver which is most repeatable and is widely understood. (11) However, under some circumstances, the T2 segment may not exist. Most focus of T2 has been for modelling purposes. For example, the steady-state roll rate or perhaps the roll mode time constant, which are adequately addressed with current techniques. Other possible T2 examples which are not addressed are motions such as AOA or load factor which Lawless notes that they do follow known patterns and are repeatable.

Capture Phase. The capture segment commences when the controls are moved from the position commanding the T2 segment. Interestingly, with no T3 segment, T1 and T2 data are considered open-loop. Therefore T3 represents the closed-loop case for transient maneuver analysis. A great deal of difficulty has been generated by definitions for capture and capture tolerance definitions. This has resulted in some interest of late. This segment represents the controllability aspect of agility or in other words the precision aspect of the agility definition. The T3 segment will likely be more complex than T1 and the complexity will be inversely proportional to the capture tolerance. Pilot aiding to capture could help here which has been suggested for carefree handling.

2.5.5.3 Agility Design Parameters

The reference 11 study was perhaps the most comprehensive to date using flight test data. Lawless noted that angular accelerations (body axis, flight path axis, euler angle accelerations) were the most common transient metrics. Butts and Lawless proposed the rise time acceleration parameter defined as " the change in aircraft attitude rate or flight path rate divided by the elapsed time since pilot input (Δ rate/ Δ time)". (11) The name was chosen because "this parameter represents the time averaged acceleration achieved when this aircraft attitude rate or flight path rate rises from one value to another".(11) The example which they used is shown in Figure 2.5.2 for the time pitch acceleration parameter. ($\Delta q/\Delta t$).

Figure 2.5.2 Time Pitch Acceleration Parameter.(11)



2.5.5.4 Frequency Domain Analysis

No existing research could be found on the use of frequency domain techniques to characterize agility. Existing techniques would be expected to gain a better understanding of the limitations of bandwidth on large amplitude maneuvering. This subject requires further investigation.

## 2.5.6 Specifying Airframe Agility

Specifications are intended to offer guidelines to designers and evaluators in order to produce an aircraft that meets the needs of the operational users. This working group feels that agility should be incorporated into the existing flying quality specifications so to ensure that in the design process good controllability is balanced with the ability to be aggressive and therefore agile. Agile characteristics are complex because pilot inputs may cause motions in multiple axes simultaneously. A brief study of the parameters used to define the agility terms in chapter 2.1 illustrate this succinctly. Some metrics though are single degree of freedom characteristics, such as a pitch angle capture. These metrics can be incorporated in existing sections of the existing specifications. The more complex metrics would perhaps best be new sections that deal with compound degrees of freedom. Of course one criticism of the metrics discussed in 2.2 has been the question of pilot aggressiveness and the possibility of less than maximum results. Perhaps lower bounds of these metrics should also be investigated as new means for characterizing flying qualities, for example Skow's torsional agility metric.(1)

The specification of agility may best be structured as transient, experimental, and operational in agreement with the metric structure developed in 2.2. Flying qualities specifications are generally for minimum performance (although some upper/lower bounds are defined) while the agility sections that would be added would state the upper performance bounds. The attitude quickness parameters are one such class of agility metric that would specify the upper bounds. When correlated correctly with flying qualities levels, provide a meaningful method of balancing agility with flying qualities. Maximization of the transient metrics fit well with existing flying qualities specifications. It has been argued by Bise and Black that agility may already be addressed in such specifications as Mil-Std-1797.(19) The experimental metrics are fairly well established as specification metrics in their own right. Finally, operational agility specifications are inherently mission task dependant and are seeing wider acceptance as valuable specification guidance. ADS-33C now includes desirable operational guidelines. This approach is also being pursued for Mil-Std-1797.

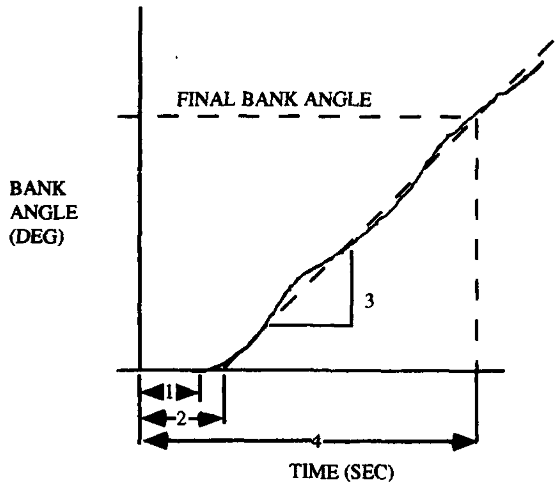
Specifying the transient agility was addressed by Bise and Black. (19) Their approach concentrated on the individual maneuver segments which make up an agile maneuver. They contend that "many researchers have largely ignored the contribution of each of these individual elements, concentrating instead on the composite"(19). In response they pointed out that existing performance and flying qualities specifications address both the component parts, total response and the final state. Focusing then on each component, characteristics can be identified to specify a level of agility. To examine the characteristics, Bise and Black identify agility as "a certain character of response (output) to pilot input(s)" (19). These characteristics were:

1) time delay from the initiation of the command to the first response of the system,
2) time from the initiation of the command or the first response of the system until the approximate steady-state response is reached,
3) the value of the steady-state response,
4) the time required to reach a final desired value,
5) the linearity of the response, and
6) the uniqueness of the response (stable, controllable, in axis of interest).

These characteristics were presented as shown in Figure 2.5.3 but are limited to single degree of freedom. In specifying agility, Bise and Black also identify controllability as paramount. From a flying qualities perspective, they note that to a pilot a set of pilot actions must provide for a response that is predictable, stable, repeatable, and in accord with the pilots training and expectations. An argument which was discussed in section 2.2. Nevertheless, in order that agility may be specified, the importance of breaking down maneuvers into specific components is

justified. Further study must be conducted for the multiple degree of freedom cases and the relation to the agility terms developed in section 2.1.

Figure 2.5.3 Agility Time History Response Characteristics.(19)




Specifying discrete elements airframe agility may be accomplished with the experimental metrics detailed in 2.2.4. These metrics are segments of tasks that are purposefully simplified so as to be controllable and repeatable. As suggested by Lawless in Reference 18, "they represented the simplest tasks that could be performed while retaining pilot-in-the-loop requirements". A necessary attribute if flying qualities requirements are to be upheld simultaneously.

Finally, mission related airframe metrics permit the specification of contribution of airframe characteristics to operational agility. The primary specification would be the time to perform a mission task element. The time would be based directly on the needs of the user. In cases where the aircraft may not be required to respond quickly then the time to perform the MTE may be relaxed. It is imperative though to convey the fact that shorter task times may be achieved with numerous techniques. A true tradeoff may not be achievable until the operational agility of the complete weapon system is studied. For example a quicker weapons solution may not be implemented with nose pointing but rather better missile envelopes or a turreted machine gun.

**2.5.7 Conclusions and Recommendations**

Gathering practical experience with agility and how it interacts with existing aircraft flight mechanical principles has begun but much still needs to be done. It is clear that bounds on agility exist and these bounds represent the maximum desirable performance that may incorporated into existing flying qualities specifications.

Simulation has developed into a powerful tool for conceptual tradeoff studies but more data needs to be gathered linking agility to design practice. In organizing this effort, the data can be obtained at three levels corresponding to the transient, experimental, and operational metric structure presented in 2.2.

The MTE has been a significant advancement in flight test practice in order to gather data on aircraft performance in operational scenarios. There appears to be a consensus now that agility, or at least experimental agility metrics, are comprised of characterizations as translational, torsional, and nose pointing metrics, although some authors emphasize specific cases. Test techniques are available for most of these metrics.

When conducting an agility flight test program, simulator rehearsals have been found to improve test efficiency. Real-time control during practice maneuvers and build-ups were also found to be beneficial. The tolerances for closed-loop capture tests need to be optimized though for the particular mission requirements.

The critical gaps are:

1) need more data linking design to agility payoffs, inverse simulations may be one method;

2) simulator visual and motion cue fidelity needs improvement to account for large amplitude motions, in-flight simulations with variable stability aircraft continue to provide important data but may have some limitations when required to achieve the agile maneuvers (including safety concerns)

3) cockpit display architectures are not optimized for agility flight testing

4) as emphasized in section 2.2, an agility rating scale is required

## 2.5.8 References

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## Chapter 3: Subsystem Implications for Agility

### 3.0 Introduction

The subject of this chapter is the agility contributions and interactions of the avionics subsystem and the weapons subsystem Although the traditional focus of agility research has been airframe agility, it must be remembered that the airframe is but one part or subsystem in a total system whose purpose is combat.

**Combat success requires more than an agile airframe.** It requires an agile weapon that can successfully control the launch transient pitch-over while maintaining target lock; it requires agile avionics systems with agile sensors that can collect and process multiple target information; and it requires an agile pilot that can utilise agile displays and cueing systems to maintain a high level of situational awareness in a highly dynamic engagement with multiple adversaries. It is just as important for a pilot to know when not to use his agility as it is for him to know when to use it. An agile airframe, by itself, is useful only in airshow aerobatics. An agile weapon system is needed for air combat. *Hence, the definition of total agility, or "Operational Agility", establishes an overall weapons system frame of reference.*

In response to the same desire to broaden the application of the agility theory to all elements of the weapon system, Boyd expanded his definition of agility in 1988: "Agility is the ability to shift from one unfolding pattern of ideas and actions to another by being able to transition from one orientation to another." This definition can be applied to the aircraft, to the pilot, or to the avionics suite with equal clarity. Boyd's definition is close to that which has evolved for Operational Agility which is presented in this report. Here Operational Agility is defined as the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness. The Operational Agility concept captures the same intent as Boyd's definition.

This definition, in combination with Boyd's "observe, orient, decide, act" OODA loop concept for the pilot/avionics element of the weapon system is utilised in figure 3.1 to illustrate how the overall concept of weapon system agility can be used to identify six individual time delays that interconnect each of the elements in the sequence of events between target identification and target destruction.

The six individual time delays are the following:

1) $\tau_1$ is the delay between the time that the threat can be observed and the time that the pilot is concious of its presence. It can be a function of many parameters, including visual acuity, target signature, sensor detection range, cueing and display formats, etc.

2) $\tau_2$ is the delay between the time the pilot is conciously aware of the threat and the time he correctly orients himself mentally to his knowledge. This time delay is cognitive in nature and can be influenced by many factors, the most important being pilot situation awareness, which can be enhanced by training. Cockpit cueing and display system formats can enhance situation awareness as well, and current research in artificial intelligence could lead to significant reductions in this time delay.

3) $\tau_3$ is the delay between the pilot's decision to take action and the actual movement of the stick, rudder, throttle or switch. This time delay is dependent only on neuromuscular effects and is typically < 300ms.

4) $\tau_4$ is the time required for the aircraft to shift from one manoeuvre state to another. Airframe agility is a function of both the manoeuvrability of the aircraft and of its controllability/transient agility.

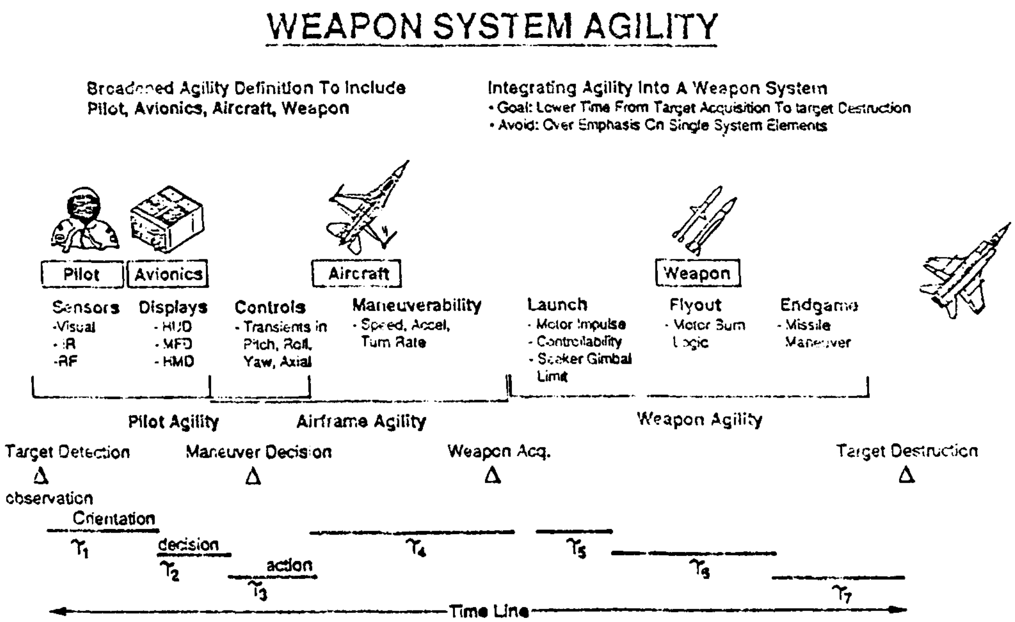
5) $\tau_5$ is the time required for the weapon to successfully transition from its stored position on the aircraft to a trajectory toward the target. For a gun, this time delay is effectively zero. For an externally carried rail-launched missile, this is the time between missile firing and the time where the missile has completed its launch transient and is successfully guiding toward the target. For an internally carried missile, the delay may include additional time.

6) $\tau_6$ is the time delay between the successful launch transient and weapon impact. For a gun, this time delay is influenced by the calibre and type of round, and for a missile, is influenced by motor impulse/burn times, missile drag and by missile endgame agility.

**Subsystem designers of agile fighters must seek to minimise each of these time delays while taking care to not suboptimise any individual one.** It is possible that over-emphasis on any one single time delay could cause other time delays to be increased, reducing the overall system agility. For instance, if post-stall manoeuvring is used to decrease $\tau_4$, it is possible that $\tau_5$ could increase to infinity due to missile launch transient problems. Also, increasing the load factor onset rate to reduce $\tau_4$ could cause the pilot to experience $g$ induced loss of consciousness, causing $\tau_3$ to increase to infinity because the pilot is asleep. Adding more sensors to the aircraft can decrease $\tau_1$, but unless the information from them is properly displayed or communicated to the pilot, sensory saturation can occur, driving $\tau_2$ up.

The foregoing total system perspective is intended to set the framework for a discussion of avionics and weapon subsystems contributions and interactions to the total agility, or Operational Agility, of the system.

**Figure 3.1**



## 3.1: Mission Oriented Systems

**(Operational Agility and Integrated Avionic Systems)**

### 3.1.1 Introduction

This section deals with the contribution of avionic systems to the overall combat success of the aircraft, and specifically, to the improvements in effectiveness to be gained with enhanced subsystem agility.

An important subject is the cost of the continuing trend of adding more capability to the mission equipment package. As combat needs cause more mission equipment packages to become more complex, the tasks associated with tending to the needs of the system consume more crew attention, at the potential cost of reduced free time for other critical tasks and reduced situational awareness. The increased opportunity for errors in planning and subsystem control can cause mission effectiveness to suffer.

In this section we will discuss the need to rely on avionics subsystem performance specification, typical avionics system components, opportunities for subsystem agility enhancement and the promise of achieving significant improvements in mission performance with the implementation of advanced automation and knowledge-based engineering.

### 3.1.2 Operational Agility Defined

From our earlier definitions presented in Chapter 1, ***Operational Agility*** is defined as the ***ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.***

The measure of Operational Agility of a subsystem or system is the measure of the time required to perform a mission task, at an agreed upon output precision for that task. It is assumed that a crew of typical ability is performing the task in the context of an operational combat mission. Operational Agility measures are workload dependent. It is possiblefor the systems's agility to decrease as the crew workload rises and allows less crew time to tend to the system, and this must be accounted for in the evaluations.

The key issues associated with measuring agility are:

*1) The specific nature of the defined task.*

Agility tasks should generally be defined as a system response to its environment to cause a desired mission outcome. A task can be defined as an action, having a measurable effect on the environment, undertaken in response to a stimulus. An example is "protect own ship from the incoming missile", a definition unlike crew tasks typically defined by cockpit designers, such as "launch flares". The difference in these two outlooks is that agility requires the design to shape the specific crew or subsystem actions to cause an outcome, where traditional design philosophy has required that the cockpit be designed to control a subsystem. In this way, the design and evaluation team can properly focus on the net effect of each item on the mission. This allows comparison of the different systems in the same general environment, since it can be assumed that the misiion outcomes are somewhat universal, even if the installed equipment and crew tasks are not.

*2) The time reqired to perform the task and its precision, measured in mission specific terms.*

The time required for the task must sometimes be treated as a variable that the crew can control. Time must be associated with task precision to be meaningful. Trials may sometimes show dramatically different task completion times, based upon crew strategies for the overall task success. For example, one crew may choose to complete a task quickly, and will allow poorer precision in the output as a necessary cost. Another crew may choose to perform the task more slowly, and perhaps with greater precision. The design team must carefully define the task as completed only when the desired mission efect has been achieved.

For example, if turning agility is being measured, a faster crew may turn more quickly, but accept poorer shot accuracy at the roll-out, resulting in shorter turn times. To allow comparison with other data runs, the time must be

carefully linked to the task completion, which in the example, may be when enough hits have been scored to achieve the kill. In this way, a slow turning crew, who preserve enough poise to achieve higher quality shots and earlier hits, may demonstrate better agility.

The specifier must carefully define all outputs in mission specific terms, with true effectiveness outputs, if genuine operational agility is to be measured. One key to look for is the test "Does the measured output sense the system's effect on its environment?" Generally, the measurement must begin with an outside stimulus and end with an external effect.

### 3.1.3 Avionics Integration

An integrated avionics system has all the key subsystems tied to common data paths (busses), controlled with central processors, and interfaced with cockpit control/display units (CDUs) and multi-function displays. Built-in-test and continuous diagnostics are routinely provided. Through integration, the data busses can provide data to all components, and the data sharing can permit a degree of flexibility and control not possible with disassociated components in conventional architectured aircraft. In more advanced aircraft, with higher degrees of automation, systems can be relatively self tending, and can adjust to varying mission conditions without crew attention.

Generally, current design specification requirements centre on individual performance of components, and on bus data rates for the integration performance of components, without specific attention to effectiveness and mission task success of the overall system. As the design progresses through its development, the degree of detail increases and it becomes increasingly difficult to analyse or measure the contribution of the subsystem to the overall performance of the total weapon system. Often, this can result in the system's behaviour as being less than the sum of all the parts, and sometimes with virtual failure.

The avionics design team must explore the lonk between the airframe, the crew, the subsystems and the mission needs to balance the design for agility.

### 3.1.4 Mission Tasks and Associated Avionics

To properly design an aircraft for effective conduct of the mission, a method of analysis must be adopted that will address the critical issues of adequacy of mission equipment functionality, appropriate system agility, and effective Pilot Vehicle Interface to assure effective combat decision making by the crew. After a series of missions are defined that make use of known threat aircraft, their capabilities, numbers, employment doctrine and tactics, and importantly, their possible future improvements in all these areas, possible system designs to perform these missions are defined. In order to systematically study the needs of the mission, it may be convenient to construct a series of mission time lines, like attachment 1, and step through the notional missions to observe the required functions of the subsystems and crew to see how they interact.

Traditional Human Factors methods, such as Task Analysis Work Load (TAWL) must be used to assure that the appropriate information is provided, that effective controls are available, and that sufficient time is allowed to make the appropriate decisions on subsystem employment to allow the crew to interact and conduct the mission. For the purposes of economy of study, it may be beneficial to take the mission time-line study and collate like functions into a list of possible actions that, though not time sequenced, allow us to examine these similar groups of related functional goals. Examples of groups which might be used are as follows:-

***Planning***, including all related functions such as route selection. This considers the mission goals and constraints and offensive and defensive attack planning. This also provides routes for Path Control implementation. It runs continuously through the mission, from Pre-Mission, reactive planning during the Mission to Mission abort.

***Survival***, including those functions to reduce detectability and reduce threat weapon effectiveness. This can include reconfiguration of systems to prepare for combat damage and interplays very strongly with the house-keeping functions. It involves Signature Management, Emission and Active/Passive sensor oversight, Masking Control, ASE/Countermeasures management, Aspect Control and Detection Control.

***Observation***, including all aspects of reconnaissance, target search and active/passive sensor control.

***Engagement***, including all aspects of target ID, allocation, control of supporting fires, weapons selection and preparation. It requires working of Friendly ID, Target Priorities and Allocation, Weapons Selection and Preparation, Weapons Launch including IFFC, Post Launch Manoeuvres, BDA/Relaunch.

***Movement***, including all location functions, controls and management of the human and automatic pilotage sensors. It executes commands from Planning, including Navigate, Flight Control, Pilotage Displays and Sensors, Terrain Following and Obstacle Avoidance.

***Communication***, including all information flow to and from one's own ship. Collation of data from all other functions is required, preparing reports on the functions, determining the appropriate radio frequency and bands.

***Vehicle Management***, including all subsystems, engine, fuel and other system consumables, except weapons. It requires maintenance of records, performance capabilities and limitations. It provides Path Control all the inputs needed to control the limits. It stores checklists and maintains weight and balance, providing displays as necessary and provides Combat and Damage Control.

**Table 3.1.1 Mission Tasks and Associated Avionics**

| **Mission Functional Requirement** | **MEP Items** | **Agility Implications** | **Associated Crew Functions** |
|---|---|---|---|
| **Mission Planning**<br>Pre-mission<br>Pro-active<br>Re-active<br>Abort | Digital map, CEOI operations order, SOP | Goal:-<br>Faster, more precise planning<br>Requires better situational awareness through better displays of more collated, meaningful information. More information is a burden, unless the data is in an immediately usable format, such as fuel in available range format, and threats as potential killers or not.<br><br>Status of team, with weapons, fuel, and susceptiblities to given threats is the most important supportive planning goal, and may most enhance planning agility. | - Assess situation<br>- Assess mission orders<br>- Fuse data<br>- Compare mission goals<br>- Devise route plans and divert and abort options<br>- Prioritise plans<br>- Allocate assets<br>- Maintain route progress awareness<br>- Maintain team plans and deviations<br>- Maintain external situational awareness |
| **Reaction**<br>Passive defence<br>Manoeuvre to avoid<br>Active defence<br>Attack<br>Reconnaissance | Missile warning<br>Laser warning<br>Radar warning<br>RFI<br>IR, RF Jammers<br>Electro-optical countermeasures<br>Decoy dispenser | Goal - Faster, more effective response to attack.<br><br>Display precise threat situation and ownship susceptibilities, sensor ranges, enhance estimation of probability of detection and/or launch.<br>Provide info. to assess avoidance manoeuvres, decoy use.<br><br>Automation of subsystems to enhance launch timing of decoys is encouraged.<br><br>Multi-ship sensor allocations will burden command and control, and reduce flexibility unless automation or displays are adapted to allow easy co-ordination. | - Monitor<br>- Assess threat type, location, potential lethality<br>- Assess proper defence<br>- Determine evasion manoeuvres<br>- Determine type, amount and launch countermeasures<br>- Determine and execute post launch manoeuvre<br>- Assess attack potentials<br>- Set sensor search<br>Monitor, adjust sensors<br>- Reconnoitre area, zone or route<br>- Record observations<br>- Formulate reports |
| | | | |

**Table 3.1.1 Mission Tasks and Associated Avionics**

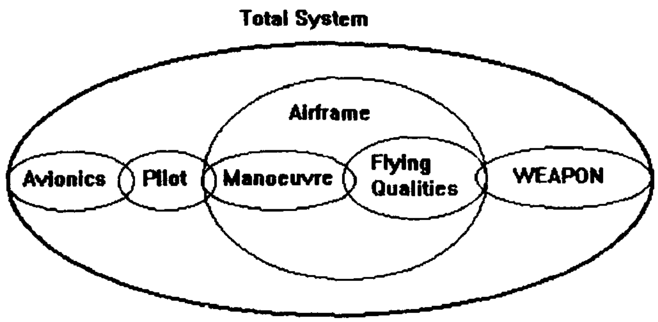
| Mission Functional Requirement | MEP Items | Agility Implications | Associated Crew Functions |
|---|---|---|---|
| **Engagement** | Missiles<br>A-A and A-S multipurpose missiles.<br>Automatic cannon.<br>Rockets, guided bombs, iron bombs, fire control. | Goal - More rapid, accurate and efficient weapons, with poised response to next target.<br><br>**Air Battle** - Display of weapons capability to enhance attack planning, and supporting closest time/space control for acceptable launch scenario, including weapons priming/repriming effects, TOF and range trades, launch manoeuvre constraints, update duration and timing, missile energy estimation for $P_k$ enhancement.<br><br>Display of threat airframe and weapons capabilities for awareness of defensive phases of battle<br><br>**Ground Attack** - Display target patterns to determine release intervals, patterns, and modes. Display most effective designation pattern, including hand-off. | - Prioritise/select targets.<br>- Select shooter (ownship, flight mate, supporting fires)<br>- Select weapons, set seekers/fuses/modes, activate weapon.<br>- Cue movement to enable IFFC.<br>- Designate<br>- Aim.<br>- Maintain launch constraints.<br>- Shoot.<br>- Maintain designate constraints. |
| **Communication** | Comm. radios<br>TRE<br>JTIDS<br>Intercom | Goals - Reduce time and error rate for target hand-off, fire clearances, IFF.<br><br>Provide fused sensor information in pictorial and alpha format, in situational context, for awareness enhancement.<br><br>Prepare reports for rapid transmission.<br><br>Control emissions in conjunction with Reaction above, for minimum susceptibility. | - Consult CEOI<br>- Select, tune radios<br>- Receive, read message<br>- Prioritise information<br>- Interpret<br>- Format reports<br>- Transmit reports<br>- Read messages |
| | | | |

**Table 3.1.1 Mission Tasks and Associated Avionics**

| Mission Functional Requirement | MEP Items | Agility Implications | Associated Crew Functions |
|---|---|---|---|
| **Movement** | Flight controls integrated<br>Flight navigation<br>IFFC<br>IFPC<br>TF/TOA<br>I2 sensor pilotage, FLIR | Goals - Support best manoeuvring and rapid/accurate weapons launch or evasion/survival<br><br>Support IFFC modes to permit crew/FC co-ordination<br><br>Display manoeuvre cues and requirements in heads up, eyes out format, especially in high AoA manoeuvres in IMC or night environment<br><br>Display target information in spatially valid format for energy management and limits observation | - Navigate along Planned path in x,y,z and time, observe consumptions.<br>- Avoid exposure to planned, unplanned threats<br>- Manoeuvre to meet Engagement, Reaction, Observation needs.<br>- Select, adjust pilotage sensors.<br>- Manoeuvre to avoid obstacles, terrain.<br>- Assess cue environment, select appropriate control laws. |
| **Vehicle Management** | Consumables<br>System monitors<br>Detectors<br>Instruments<br>Diagnostics<br>Cautions and warnings | Goals - free crew to attend external situation by reducing or eliminating housekeeping.<br><br>Maintain consumables control, including fuel, decoys and weapons and display usages in mission formats.<br><br>Display subsystem health by exception, with status shown in mission affecting format for rapid replanning and reconfiguration. | - Determine and maintain weight and balance state.<br>- Estimate flight performance, available range, consumable allocation.<br>- Determine, observe limits.<br>- Monitor all subsystems, estimate states, diagnose, isolate failures, perform proper procedure changes.<br>- Note environmental changes, new system requirements.<br>- Determine new performance.<br>Determine take-off, landing, hover performance. |

## 3.2: Weapons

Chapter 1 and 3.0 suggest that "total" system agility is made up of many component subsystems each having its agility contribution to the total system. *Emphasis on the agility contribution of any one component has the tendency to show the weakness of the other components.* In this environment of increasing emphasis on component agility, it is useful to think of total system agility, or Operational Agility, as a chain with many links.



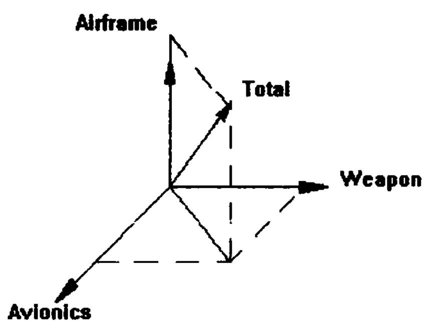

*It is instructive to recall the the emphasis on agility began as a result of increases in WVR (IR) missile technology/agility, i.e. the all-aspect weapon.* As fighter pilots in reality fight weapon envelopes (not really aircrat), this dictated a revolutionary change in WVR tactics placing great emphasis on achieving the first shot from any aspect that measurably decreased the combat time line that pressed the need for *increased airframe agility*. However, the increased emphasis on airframe agility has resulted in airframe technologies that produce rapid, high angles of attack (AoA), i.e. Supermanoeuvrability, that can result in current missile inventory failure due to tip-off or sensor loss of lock. New supermanoeuvre missile designs (Archer 11, AIM-9X) are attempting to solve this agility need but, at the same time, are pressing on the avionics agility to supply the necessary situational awareness in the presence of supermanoeuvrability to make use of the expanded envelopes of supermanoeuvre missile designs.

***Overemphasis on any given agility component link may in fact result in a "break" in neighbouring links,*** such as:-

| Agility Link Increase | Link Break |
| --- | --- |
| Weapon (All aspect) | Airframe |
| Airframe (High $E_m$ or Supermanoeuvre) | Pilot g-LOC<br>Pilot Disorientation<br>Weapon Tip-Off |
| Weapon (Supermanoeuvre) | Avionics (Situational Awareness) |

Although there are other components in the total system agility vector, airframe, weapons and avionics are the major ones that must be balanced so as not to produce a break in the agility chain and yet maximise the total system

**System Agility Vector**




agility. *The air-to-air weapon is key as it is the main driver in how the pilot devises tactics to employ the total system.* As such, consider the impact of the following weapon characteristics:-

How do sensors and weapons drive tactics and agility needs in other system components?

How important is having the "first shot" (in light of mutual kill considerations)? What specification (shot time advantage) is reasonable for the missile timeline?

What are the relative contributions of airframe agility v weapon agility? Off bore sight?

Each of these questions involving the weapons subsystem is addressed in paragraphs that follow.

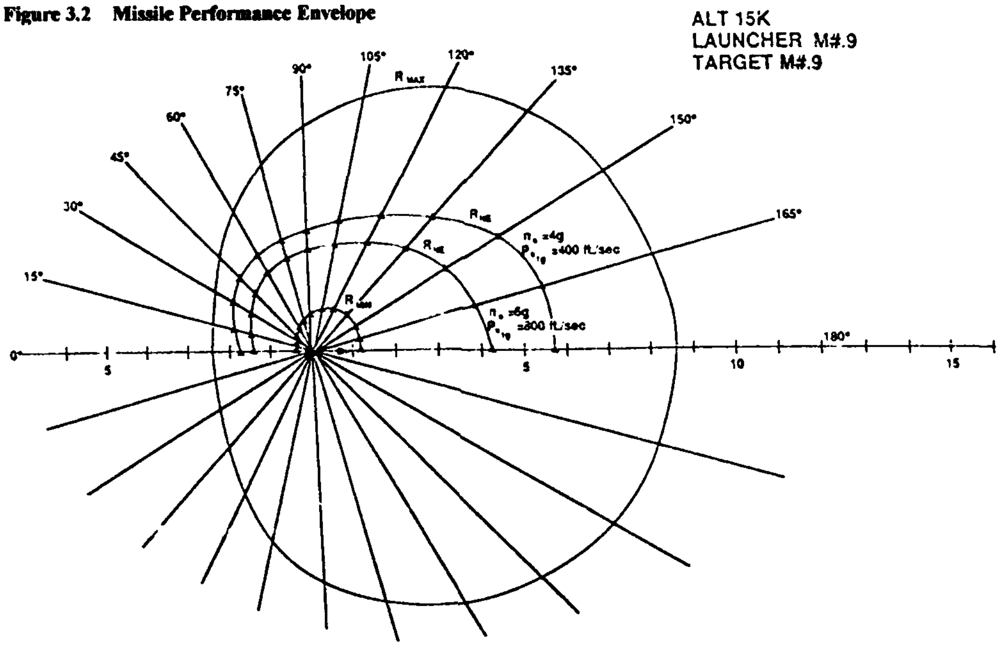
**3.2.1 Weapon Envelope, Tactics and Agility**

As mentioned in Paragraph 3.2, advances in IR missile sensor technology made possible all-aspect missile launch that previously was limited to tail-aspect. This brought about a significant change in WVR air-combat tactics, shifting emphasis from sustained, often lengthy, turning air combat to rapidly pointing the nose to achieve the first shot aspect. This greatly compressed the air-combat time-line highlighting the need for airframe technologies (i.e. high transient agility, thrust vectoring, forebody vortex control, supermanoeuvrability) to rapidly move both the velocity vector and aircraft nose. *This is a current example of the great influence of an advance in weapon agility having significant impact on the airframe and its associated tactics. Supermanoeuvre missiles will produce yet another revolutionary change in the future.*

It must be remembered that the lethal zone (kill zone) of an air-air missile is the intersection of its performance envelope(i.e. missile energy/kinematic limits) with its capability to sense a target (i.e. a combination of sensor power/coverage and target signature). A generic missile kinematic performance envelope is shown in Figure 3.2 with the characteristic $R_{max}$ (maximum range), $R_{min}$ (minimum range) and $R_{NE}$ (range no escape). $R_{max}$ is usually associated with an energy (minimum missile velocity for terminal manoeuvre) limit, $R_{min}$ is usually associated with a guidance enable/safe arming time and $R_{NE}$ is the boundary range of kill when the target manoeuvres for missile evasion at sustained load factor. $R_{NE}$ is typically 40% to 60% $R_{max}$. This kinematic performance envelope is based on a lead-pursuit guidance course that requires the pilot to appropriately lead the target at launch.

As would be expected, $R_{min}/R_{max}$ values vary greatly with the velocity magnitudes of the combatants. The combination of constantly changing combatant velocity vectors presents highly dynamic missile performance conditions to the pilot that *presses on the agility of the avionics subsystems* to present up-to-date weapons envelope information that the pilot can use effectively. Complicating knowledge on the state of the missile kill zone is the combined impact of sensor (avionics) and target signature. One obvious objective of "stealth" (an airframe technology) is to reduce RF/IR/visual signature to shorten detection ranges thereby negating useful employment of

**Figure 3.2 Missile Performance Envelope**




the kinematic performance potentials of missiles. Technology advances instealth, sensors and missile kinematic *performance* (*supermanoeuvrable*/thrust vector missiles) are producing dramatic changes in the lethal (kill) zones of missiles that will continue to drive the agility need of avionics, weapons, airframe and the tactics to best employ the total Weapon system. Although there is currently limited coupling of airframe tactics and signature control (i.e. chaff, flares and throttle control for IR signature), near term technologies will no doubt increase the interaction between signatuer control and aircraft tactics to avoid detection.

It is clear from the foregoing discussion that there is a high interaction between the "agility" of the avionics, weapon and airframe subsystems that also impact pilot tactics. The subsystem designer can no longer "design in a vacuum" and neglect the potential impact of his subsystem on the total system.

**3.2.2 First Shot Considerations**

Although most fighter pilos are by nature aggressive/offensive, there is a great motivation in all pilots to survive to fight another day. As such, the "first shot" and a missile bearing down on the average pilot can cause him to rapidly shift from offense to defense. Just having an aircraft nose pointed at you in an adversarial air-combat situation can be threatening. In this environment, *any shot-time advantage can be a real tactical advantage*. Shot-time advantage can result from any system component whose end result is pointing/angular/range advantage on an adversary that brings the missile launch constraints within acceptable conditions. As an example, consider the following technology areas that can enhance achieving missilie launch conditions more rapidly:-

| Technology Area | Angular Effect | Subsystem |
| --- | --- | --- |
| Improved thrust/weight<br>Lower wing loading<br>Controlled high angle of attack (supermanoeuvrability)<br>Thrust vectoring through the centre of gravity | Improved turning of velocity vector | Airframe |
| Thrust vectoring<br>Forebody vortex control | Rapidly point nose about velocity vector | |
| Improved sensor sensitivity | Increased acquisition range at any angle | Weapon/Avionics |
| Improved seeker field of view | Off boresight acquisition | |
| Reduced static margin at launch | Reduced missile tip-off | Weapon |
| Thrust vectoring | Enlarge region of acceptable launch constraints and kinematic envelope size | |
| Computer generated dynamic weapon envelopes | Accurate knowledge when missile launch constraints are met | Avionics |
| Stealth | Deny detection at any angle | Airframe |

Any of these technology areas can promote a shot-time advantage over an adversary.

What, however, would be an acceptable specification of shot-time advantage (over a specified threat) that system designerscould use as a guideline?

The most conservative approach in WVR air-combat would be to set the shot-time advantage specification to the fly-out time of one's own missile. In BVR air-combat, a conservative approach would be to set the missile f-pole value to $R_{max}$ of the threat weapon subject to sensing of its adversary. These very conservative approaches to a shot-time advantage specification result in missile/target impact before the target/threat can respond. Perhaps a less demanding specification (i.e. 50% of missile fly-out time, etc.) would be sufficient in light of pilot defensive reaction to first shot. The analytical relationships of shot-time advantage/f-pole to the affording technologies are easily modeled with the basic equations for aircraft turning performance and/or sensor target signature detection. For example, any technology that produces a WVR angular advantage (i.e. supermanoeuvrablity, off-boresight, etc.), the shot-time advantage (STA) relationship is

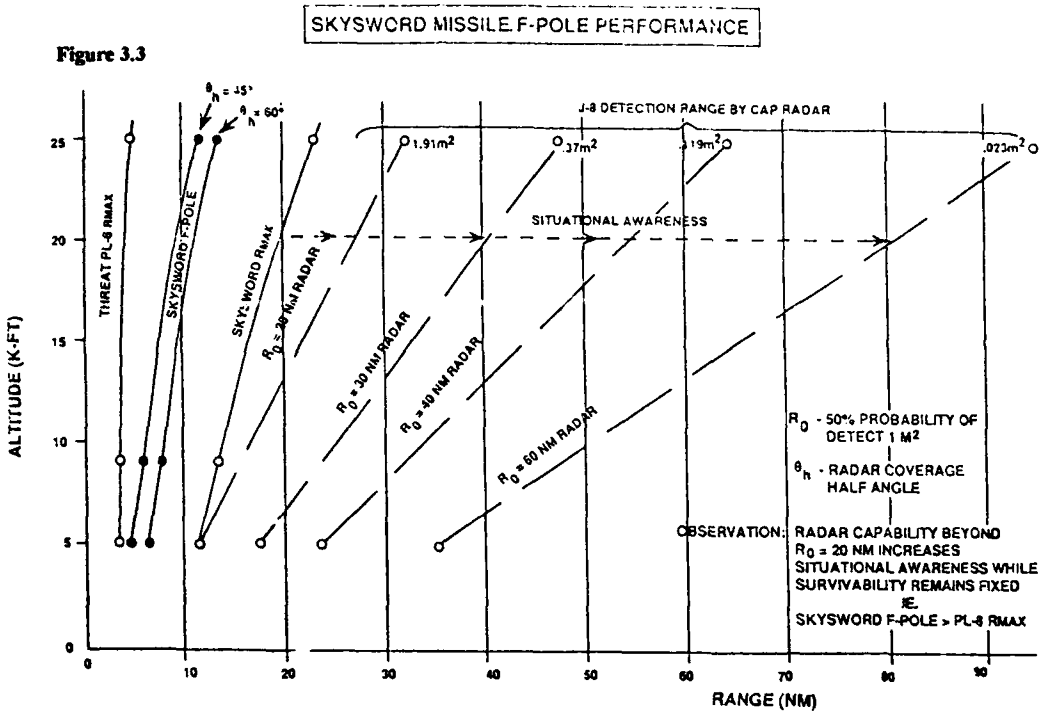
$$\text{STA} = \frac{\text{Angular advantage over adversary}}{\text{Turn rate of adversary}} \qquad (1)$$

Consider WVR turning air-combat (assumed neutral state at start) of two aircraft each having the same sustained turn rate ($\approx$12°/sec) but one supermanoeuvrable to 70°AoA with a missile capable of launch at 70°AoA. Further, assume that the maximum AoA of the adversary is 20°. The shot-time advantage from equation (1) is therefore

$$\text{STA} = \frac{70 - 20}{12} = 4.17 \text{ sec}$$

Figure 3.3 shows the key relationships affecting f-pole in a head-on BVR engagement of an F-5/Skysword system with a J8-Mig 23/PL-8 threat. Data is based on Jane's information. As can be seen, an F-5 radar $R_0 \approx 20$ nm provides sufficient detection beyond the Skysword $R_{max}$ resulting in maximum use of the Skysword kinematic weapons envelope. Skysword f-pole values are in excess of the threat PL-8 $R_{max}$. Improved radar size beyond $R_0$ =

Figure 3.3




20 nm can provide either additional situational awareness against the J-8/ Mig 23 threat or margin against threat signature reduction. For example, improving the F-5 radar $R_0$ from 20 to 40 nm improves situational awareness an additional 28 nm against the J-8/Mig 23 or allows threat signature reduction to 0.119 $m^2$ and yet employ the Skysword missile at its $R_{max}$. In this BVR example, the main subsystem interactions are weapons envelope, avionics (radar power/coverage) and airframe (signature).

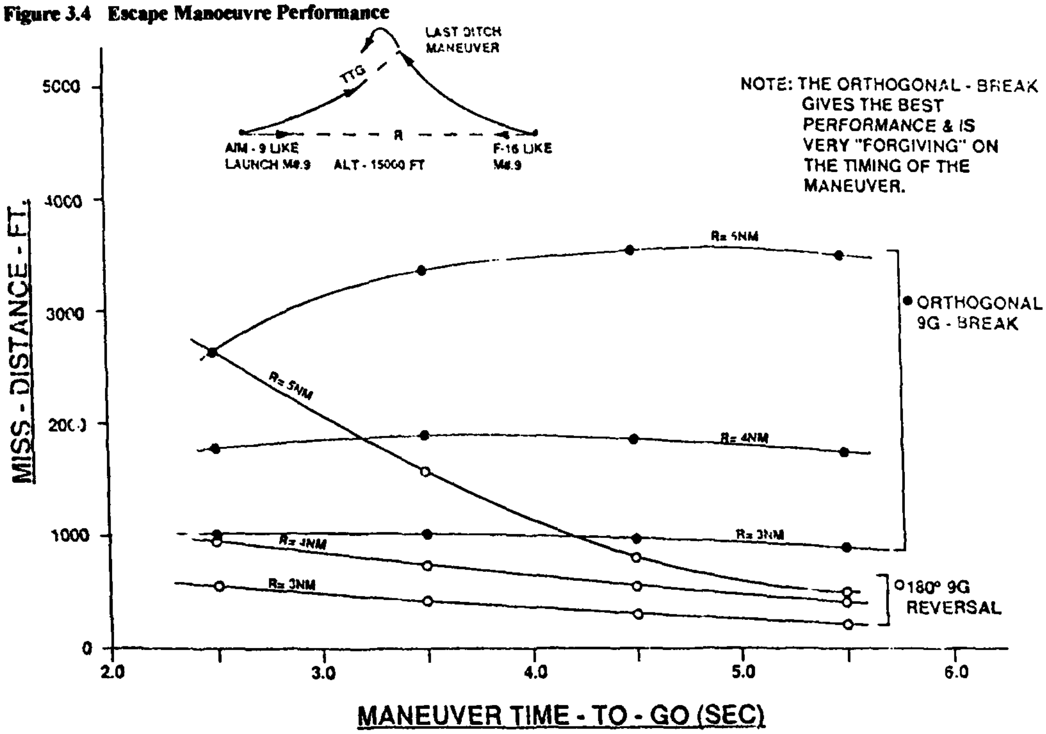
Although agile avionics, airframe and weapons subsystems play a major role in offense, an agile airframe (and to a lesser extent avionics) plays the major role in evading a threat missile. If avionics (and/or visual sighting) can provide warning information outside $R_{NE}$ and if the tactical situation will allow it, the basic evasion tactic is to turn away at sustained load factor and outrun the attacking missile. Inside $R_{NE}$, the accepted evasion tactic is to "beam" the missile (to cause the missile to pull load factor and lose energy) and at the appropriate "time-to-impact" change the aircraft manoeuvre plane and pull maximum load factor to increase the missile miss distance. As can be seen, increased airframe agility (high sustained turn rate and high roll rate about the velocity vector at maximum load factor) plays a major role in missile evasion.

Avionics also plays a role in providing warning and cues when/how to manoeuvre.

Figure 3.4 shows a sample relationship between manoeuvre time-to-go, initial head-on range, R, and miss-distance for two types of "last ditch" manoeuvres: 180° 9g reversal, orthogonal 9g break. As can be seen, the orthogonal break produces the largest miss-distance in the 3 - 5 nm initial range which is the heart of an AIM-9L-like envelope. Furthermore, the miss-distance curves are generally flat and insensitive to time-to-go which allows for error in timing the "last ditch" manoeuvre. This could relax the required accuracy of avionics that would aid pilot judgement of the time window for the "last ditch" manoeuvre.

*In this defensive example, it is interesting to note how the airframe, avionics and pilot/tactics subsystems are highly interactive.*

Figure 3.4 Escape Manoeuvre Performance




### 3.2.3 Airframe v Missile Agility

Although a balance of agility between avionics, airframe and weapon subsystems appears necessary in a normal system design, one can envision a system with an extremely agile/manoeuvrable missile coupled with highly agile avionics (for situational/weapon envelope awareness) that could relax agility demands on the airframe/pilot. These potential subsystem agility options suggest alternatives to achieving high total agility that may have cost disadvantages and causes one to pose the questions:-

Which subsystem(s) results in the most agility enhancement for a given cost investment?

Is it more effective to invest in agile missiles or agile airframes?

Figures 3.5 and 3.6 show some analysis results that suggest that nominal missile agility enhancement operational effects may be more costly to achieve with equivalent airframe agility enhancement. A Blue F-16 like aircraft formed the baseline for the airframe agility enhancement. A Red AC-77 was created for the threat that had:-

1) Improved "manoeuvre efficiency" (i.e. higher $P_s$ at maximum load factor).
2) Missile with 10° - 20° off boresight launch capability in a lag tactical situation.

Four airframe agility enhancements were applied to the Blue F-16 baseline as follows:-

1) An improved engine (ATF like) with around 10% more maximum thrust.

2) Increase the stall AoA 8° and double the transient/functional agility.

3) Allow the thrust vector to act through the c.g. and gimbal forward 110°.

4) Add thrust vectoring to allow supermanoeuvre to 70° AoA and include low static-margin missiles that will not tip-off at 70° AoA.

**Figure 3.5 WVR Average Blue Angle-Off Advantage**

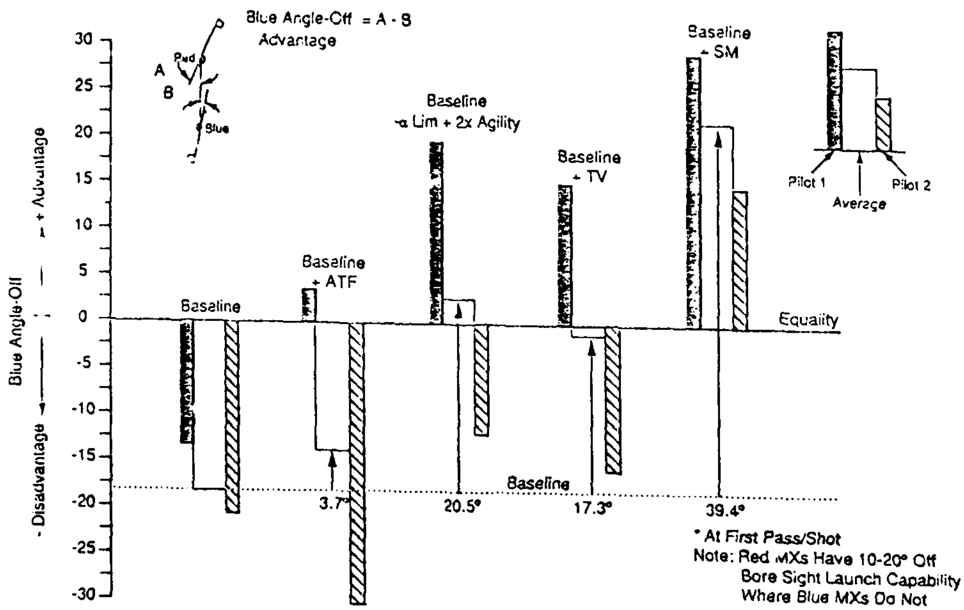



**Figure 3.6 WVR Exchange Ratio v Technology**

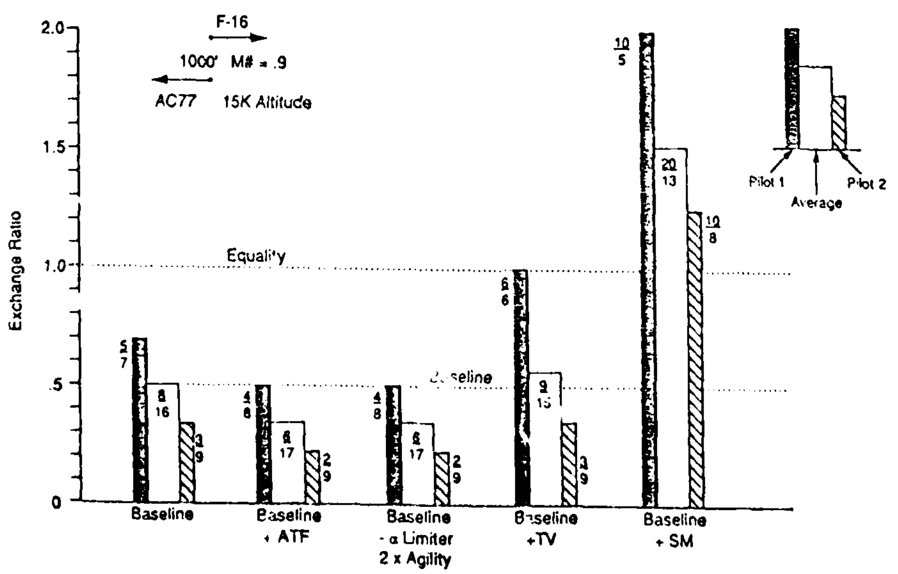


Figure 3.5 shows the Blue angle-off advantages/diadvantages of the baseline and various agility airframe technology enhancements. As can be seen, the improved "manoeuvre efficiency" of Red results in a Blue angle-off disadvantage of around 18°. Table 3.0 compares the Blue angle-off advantages with the corresponding exchange ratio results for each airframe technology agility enhancement.

**Table 3.0 Airframe Technology Results**

| | Airframe Technology | Blue Angle-off Advantage | Exchange Ratio |
|---|---|---|---|
| 1) | Baseline | -18° | 0.50 |
| 2) | Baseline + 10% thrust | -18° + 3.7° | 0.35 |
| 3) | Baseline + 8° AoA stall and 2 x Functional Agility | -18° + 20.5° | 0.35 |
| 4) | Baseline + thrust gimbal through c.g. | -18° + 17.3° | 0.60 |
| 5) | Baseline + supermanoeuvre to 70° | -18° + 39.4° | 1.54 |

It is interesting to note that Items 3 and 4 result in near equality of angle-off advantage with Red, yet the exchange ratio shows little enhancement. This is due to the Red 10 - 20° off-boresight missile advantage. Supermanoeuvrability to 70° AoA with non tip-off missiles results in a 20° Blue angle-off advantage over Red sufficient to counter the 10 - 20° off boresight capability of Red's missiles shifting the exchange ratio in favour of Blue to 1.54. Although much more analysis would be need to be done (to include cost analysis) to be objective, these cursory results subjectively suggest that the Blue airframe agility enhancements that counter the Red missile off-boresight advantage are more costly than the added cost for the missile enhancement.

### 3.3: Subsystem Agility Metrics

It is clear that the subsystems and weapons will impact the agility of the total aircraft system as does the airframe. In order to design in characteristics to achieve quick and precise responses, metrics must also be developed for subsystems and weapons. This subject has not received much attention in any literature.

The metrics would be expected to characterise the concepts embodied in the following definitions·

> ***Systems Agility*** is the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.
>
> ***Weapons Agility*** - the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures.

As with airframe metrics, the quickness and precision are critical elements of these definitions.

#### 3.3.1 Application of the Operational Agility Metric Classification Structure

The diverse requirements of the design, evaluation and operational communities to organise the agility data being gathered were consolidated with the airframe agility metric structure developed in Chapter 2, Section 2.2. The example presented in Chapter 2, Sections 2.2 and 2.5 focused on the airframe aspects of the overall contribution illustrated by Figure 3.1 but lacked detail for the target acquisition and missile launch segments ofthe time-line. To focus deeper on the individual contributions of the sensors and weapons systems, discrete task elements and instantaneous characteristics are conceivable. From this perspective, avionics and weapons experimental and transient metrics as well as global operational metrics can be constructed. Furthermore, the concept could easily be applied to other mission task scenarios where time is considered critical and the avionics and weapons systems play a major role. It appears that the OA metric structure can be stretched to encompass the airframe, avionics, weapons and PVI. This acn be implemented with each subsystem individually with transient and experimental metrics followed with a build-up in complexity to the total aircraft with operational metrics.

The hierarchical nature of the metric classification scheme can be combined with the main elements of Operational Agility as shown in Figure 3.7.

In general terms, operational metrics focus on long-term events, experimental metrics focus on short term events and transient metrics focus on instantaneous events. Since the idea of susbsystem and weapons agility metrics is in its infancy, it is difficult to detail clear facts. The following comments can, however, be made regarding each class of metric:

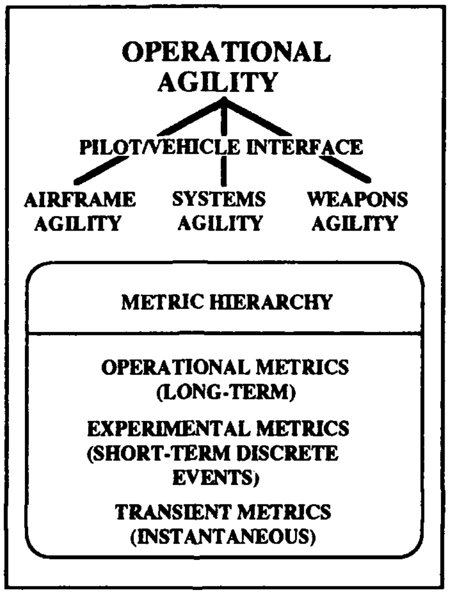
**Transient Metrics.** With weapons and especially avionics, the broad definition of subsystems given by this working group are not easily unified by a single theoretical basis that is adaptable to transient metric characterisations as is possible for flight mechanics. Subsystems involve electromagnetic signal, information flow, missile and weapon flight mechanics making the transient metric concept difficult to characterise. This aspect requires further study.

**Experimental Metrics.** Development of experimental metrics is somewhat easier as subsystems lend themselves to functional task analysis principles as described in Chapter 3, Sections 3.1 and 3.2. Experimental metrics will tend to be *system specific*, e.g. radar, FLIR, PVI, defined at a finer level of detail. The characteristics applicable to agility will be those associated with the time to perform a function, for example, time for a radar beam to slew to a particular azimuth or elevation.

**Operational Metrics.** Operational metrics will tend to be *global and mission specific* as were airframe metrics. Global metrics will be the time to perform an MTE, accuracy, and perhaps aggressiveness ratings. Mission specific metrics could be best organised as per the functional goals in Section 3.1.5: planning, reaction, observation, engagement, movement, communication and vehicle management.

Research on system and weapons metrics must be done or adapted from existing knowledge databases. This will require greater interaction between designers specialising in all fiels implicated by these concepts. As with airframe metrics, the focus of the research should be along the lines of mission tasks that require quick responses.

**Figure 3.7 Operational Agility Hierarchy**




### 3.3.2 Air-to-Air Radar Agility Metrics

A simple example of the application of the OA metric structure to subsystems is the air-to-air radar. Traditionally, the sophistaication of many radars make it very difficult to identify non-technology dependent metrics. The strength of operational agility analysis of the radar is that the delay of the complete system to conduct specific tasks can be characterised from a top-down perspective.

The operational agility of the air-to-air radar is promarily due to the operator control/display device, antenna beam sweep characteristics and signal processing delay. The agility of the beam is described by its ability to change in direction or transmitted signal waveform. (Reference 3.3.1).

Transient, experimental and operational metrics can be defined to characterise the radar's agility. Possible metrics in each class are:

**Radar Transient Metrics** are well established for radar signal analysis in the time and frequency domain.

**Radar Experimental Metrics** for the antenna are: time to change boresight elevation and azimuth; and time to change beam pattern. The signal processing delays are associated with: beam setup; transmit signal waveform setup and modulation; time of flight; demodulation; counter-counter measures processing; specific analysis processing; and display presentation processing. Since radar designs have numerous options (e.g. mechanically steered antenna

or phased array antenna) these delays should be generalised as: time to setup beam and transmit the desired signal: and time to process the return and display the raw data. An extension of the concept would be required if the radar signal data was sent to a sensor fusion component with an added delay prior to presentation to a pilot or a pilot's associate. Both the transient and experimental metrics can be evaluated in laboratory or anechoic chamber environments possibly with the radar broken down into its component parts.

**Radar Operational Metrics** are: time to acquier, identify and lock-on to a target or series of targets. These metrics include all the characteristics of the antenna, signal processing and display functions. These metrics should be evaluated in the real environment. It is up to the evaluator to define the specific mission scenario: radar target geometry (elevation angle, azimuth angle, range) and target radar cross section. For valid results, further stipulations may be required, such as a range at less than maximum detection range for the particular radar cross section chosen for the test.

These concepts need a great deal of study and development. The rapid prototyping approaches used by several major aircraft system integration companies are directly applicable to system and weapon agility.

### 3.3.3 References

1) C.Beal & B.Sweetman
Fighter Radar in the 1990s
International Defence Review 8, 1992

## 3.4 Rapid Prototyping

The objective of an agile system is to be quicker and to respond to a changing combat environment. Modern rapid proto-typing to integrate avionics has become an enabling technology for achieving this objective. This has essentially been achieved by making the information flow more logical and easier to use. The information flow involves several different paths. These are:

> **inter-system** by way of the data bus communication and sensor fusion.
>
> **system-pilot** by way of the PVI as will be discussed in Chapter 4.
>
> **inter-crew** through the intercommunication system or perhaps the integrated display system.

Failure to quickly pass information in the integrated system will have an impact on the agility of the total aircraft. Furthermore, continual pressure has been exerted by the individual avionic systems for more data bus bandwidth. This trend will increase data throughput and therefore reduce time delays.

The design of highly integrated aircraft avionic systems has only matured recently. Traditionally, development techniques used for airframe prototypes were applied. This resulted in the integrated system being developed well after each specific system had been developed. The avionics development lagged the airframe by several years in most cases. The integrated system was flight tested with only a small amount of ground testing. These integrated systems were fraught with problems and the "fly-fix-fly" syndrome. As computer architectures matured and progressed it became obvious that ground testing using spread benches and simulation facilities were more cost effective and time efficient than flight testing. Modern crew station design has now evolved to a point where the integrated system is developed concurrently with the airframe and is tailored more closely to the tasks for the specific mission of the aircraft.

One example of this approach is the Sikorsky crew station design for the Coamnche helicopter. Concurrent engineering techniques are being applied. Three fundamental philosophies were used to tailor the integrated systems functions:

> **Aggressive pilotage** should be enabled in order to "**move to survive**".
>
> **Minimise housekeeping** in order to keep the crews mind on the mission.
>
> **Avionics tailored to the mission** so as to "**fight the threat not the avionics**".

This philosophy was implemented in the design process that had the added benefit of reducing time delays. Superfluous information can be eliminated to minimise crew task saturation.

Other capabilities that aid in this process are facilities such as the Integrated Facility for Avionics Systems Test (IFAST) at Edwards AFB and the Air Combat Engagement Test and Evaluation Facility (ACETEF) at Patuxent River. These facilities use simulation and emulation to test integrated weapons systems in the electromagnetic environments that are easily controlled but not easy to reproduce in flight test.

A more agile total system is therefore a by-product of crew station rapid prototyping. More research and development is required to completely describe the process associated with concurrent integrated avionic system design.

### 3.5 Sub-System Agility Conclusions and Recommendations

Pilot tactics to employ a total weapons system are highly coupled into the usable portion of the weapons envelope defined by the capability of on-board sensors to acquire and track a target and provide the pilot situational awareness. Future tactics BVR will be driven by a high interaction between capabilities in avionics, sensors, weapons envelopes and stealth. WVR tactics will be driven similarly but greatly complicated by new fighter aircraft control effector technologies such as high AoA/thrust vectoring. Such technologies will force innovation in how to train pilots cost effectively to employ these systems.

From this discussion of sub-system agility, the following conclusions may be drawn:

1) Combat success requires more than an agile airframe.

2) Caution should be exercised when focusing on the time delay contribution of each aircraft sub-system so as to avoid over-emphasis on any one time delay potentially leading to increased time delays by other components.

3) Clearly understanding the time delays for mission functions enables identification of actions to automate (e.g. housekeeping) leaving the crews limited time to more critical tasks such as the tactical situation.

4) Knowledge engineering concepts can assist in crew response to a changing environment.

5) Combatants with constantly changing velocity vectors result in dynamic missile envelope conditions which press on the agility of the mission systems to present up-to-date information.

6) The metric structure of Chapter 2, Section 2.2 can accept weapons and sub-systems agility metrics.

7) Sub-system agility concepts require extensive development.

8) Rapid crewstation prototyping represents an enabling technique for enhancing the ability of an aircraft to respond to a changing environment.

9) The design process must ensure that the weapon and airframe envelopes are compatible.

It is recommended that sub-system agility concepts are developed further.

# Chapter 4

## Pilot/Vehicle Integration

### 4.0 Overview

Aircraft cockpit designs for operational agility must respond to numerous requirements beyond those associated with earlier high performance aircraft. Pilot constraints based on physiology, information transfer, and mission planning must be overcome to take full advantage of new agile systems.

Overcoming constraints associated with high angular rates, accelerations, and onset rates make heavy demands on pilot and life-support systems. Removing constraints in angles of attack and in weapon launch envelopes require display technology to allow the pilot to fly using references well beyond the field of view of his Heads Up Display (HUD). The pilot must not be constrained by reduced visibility through display and protective devices. High data rates from numerous sensors and offboard sources require efficient displays, conveying maximum information to the pilot in minimum time, with minimum distraction, and in as natural a manner as possible. If all else fails, ejection from an unconstrained flight envelope makes additional demands on egress systems.

Complex scenarios requiring engagement of several targets simultaneously mandate some degree of pilot aiding to free the pilot of situational awareness constraints. Pilot aiding must be accomplished in a manner to free the pilot to work on the most important tasks, usually tactics and top level mission management. Meeting the pilot's need to command and control equipment quickly and accurately requires exceptional ergonomics and advanced pilot-interface technology.

### 4.1 Physiology

Whether driven by high-maneuvering performance or superb agility, it is evident that the agile aircraft's cockpit must accommodate high linear and angular rates, accelerations, and onset rates. Among the concepts in use to provide physiological support to the pilot are reclined seats, positive pressure breathing, more complete anti-g garments with sophisticated, flight control system-operated actuation systems, and advanced pilot-training systems. However, extended periods at elevated acceleration levels may still have deleterious physiological effects.

#### 4.1.1 Anti-g Protection

Reclined seats are used in the F-16 and the Rafale, adding about 1/2 g to the pilot's tolerance. These seats are packaged to fit into smaller cockpits, allowing the designer to reduce total airplane size. However, consideration must be given to the display size and its position when reducing the airplane size. The drawback of the reclined seat is that it becomes more difficult for the pilot to *check six*, although pilots accommodate this difficulty admirably. An alternative is the articulated seat that reclines in the high-g environment, but is otherwise upright. This seat has been ground tested, but complexity, weight, and potential failure modes have kept it from being accepted to date.

Positive pressure breathing, augmented by balanced external pressure to prevent over-distention and assist in exhalation, has been proven to add to g tolerance by reducing pilot workload associated with counteracting g loads. The system consists of a regulator that schedules mask gas pressure with g and a vest that automatically pressurizes to balance the increased pressure in the pilot's lungs. The result is a system that allows maximum oxygen uptake, while at the same time, helps the pilot strain to force blood from the abdomen toward the eyes and brain. By adding anti-g trousers with more complete coverage than current g

suits, additional g tolerance is achieved with substantially less pilot fatigue as compared to a cutaway g suit and a straining maneuver.

A two-fold training approach has been shown to improve pilot g tolerance. The first approach is to make sure that each pilot uses the proper straining technique in a high-g environment. This technique can be conducted in a man-rated centrifuge where the pilot is subjected to the g environment while accomplishing a tracking task.

The second approach is physical fitness training. Fitness training is used to increase muscular strength and the ability to maintain a high blood pressure by muscular straining for extended periods during lengthy engagements. Strength training with weights is normally recommended. Aerobic conditioning is only recommended in very moderate amounts for pilots requiring high-g tolerance because it tends to lower the blood pressure.

#### 4.1.2 Angular Rates

High angular rates and accelerations may also affect pilot performance. Little research exists to quantify such an effect. Pilots performing spin tests have shown a high degree of tolerance to angular rates exceeding those developed in aerodynamic flight by current aircraft. On the other hand, the *coriolis effect* leading to vertigo suffered by pilots under instrument conditions during head rotation in more than one axis suggests a different conclusion. The likely explanation for the difference is that the spin test pilot is exceptionally careful to develop and maintain visual reference. The pilot of an agile aircraft in operational use may not have the opportunity to maintain strong visual references. Research on the effects of high angular and linear rates and accelerations under various conditions of visual reference is needed.

#### 4.1.3 Situational Awareness

Hand in hand with g tolerance and vertigo, situational awareness must also be considered. The importance of situational awareness cannot be overemphasized. Maintaining situational awareness correlates very strongly with combat success and should be an important objective in the design of the crew station of the operationally agile fighter.

Physiological causes are not the only reason for loss of situational awareness. Loss of situational awareness may result from overstimulation -- too many inputs -- or from understimulation -- not enough input. Loss of situational awareness may be manifested as misunderstanding the tactical situation, misinterpretation or lack of perception of sensor inputs, or loss of awareness of flight conditions. Situational awareness is a cumulative phenomenon that may have several simultaneous causes. Past events suggest that pilots may experience loss of situational awareness without encountering confusion or being otherwise aware of the circumstance.

Anecdotal evidence from physiological experiments suggests that under high-g conditions, but without loss of consciousness, decreased ability to process information may occur. Additional research needs to be conducted to determine the relationship between sustained high-g (below the level causing loss of consciousness) and the loss of situational awareness.

##### 4.1.3.1 Data Overload

High data rate conditions can result in pilot sensory overload and increase the risk of loss of situational awareness. When in sensory overload, pilots may process information in the order that it arrives rather than in priority order. Subjects are often unable to recognize their overloaded state. Further physiological and psychological research is warranted to better define the phenomena and improve the ability to cope with them.

#### 4.1.4 Flight Conditions

##### 4.1.4.1 High Angle of Attack Flight

Productive use of a capability for high angle of attack requires that the pilot be able to operate his aircraft as well as aim and fire weapons in highly dynamic environments. High-angle-of-attack flying in itself presents

significant challenges. For years pilots have been able to assume a fighter was usually headed about where the fighter was pointed. Recent technology, allowing controlled flight above a 40-degree angle of attack, has changed this situation. Pilots of high-angle-of-attack aircraft have significant difficulty determining flight path from current displays. One interesting phenomenon is that at about a 45-degree angle of attack and above, airplanes may appear to the pilot not to be reducing the angle of attack in response to nose-down pitch commands. Instead, they appear to maintain the angle of attack and change the flight-path angle; this is not intuitive to the pilot and is counter to his training for stall recovery.

New high-angle-of-attack technology allows the pilot to fly at conditions where the flight path is well out of the HUD field of view. Helmet-mounted displays can provide a solution, but are now only being certified for ejection-seat aircraft. Even when these displays are available, some issues remain unanswered. For example, if the pilot is not looking in the direction of flight, limitations of the HUD are not overcome by the helmet-mounted display. At a 60-degree angle of attack, the pilot would need to look at the cockpit floor to *see* flight path. Knowing that the flight path is through the floor may not be very useful if the pilot is at an angle where he can't *see* where the aircraft is going. A display system that allows the pilot to *see* through the structure of the cockpit may be necessary to fully address issues of situational awareness at a high angle of attack.

Depending on the circumstances, it may not always be of primary importance for the pilot to be aware of flight path. Maintaining awareness of his relationship to other aircraft and of the fields of regard of his sensors and weapons may be of much greater importance.

#### 4.1.4.2 Multimission Flying

Pilot-interface technology will be further stressed by new mission capabilities. As multimission aircraft proliferate and training opportunity decreases, keeping a pilot fully proficient in all possible fighter missions will be a challenge. Pilot-aiding systems may provide an answer. Initially, such systems might be oriented toward safety. One dilemma in the development of these systems is determining how to keep them from interfering with the pilot's intentions. Pilot overrides can be provided for all pilot-aiding systems, but such an approach must be used judiciously. If a pilot becomes accustomed to frequently and easily overriding the system during normal flight, he is unlikely to use the system's capabilities in more extreme situations.

An extremely difficult aspect of multimission flying is maintaining awareness of the capabilities of weapons and storing and using them properly. Missile parameters become an exceedingly complex equation of relative angles, speeds, and altitudes. As advanced air-to-surface weapons are developed for high-threat environments, the same situation will present itself. Netting with other aircraft for sharing of information and mission responsibility can result in a substantial increase in mission capability, but at the expense of requiring the pilot to deal with evermore complex situations. The nominal set of rules used by the pilot-aiding system should be selected by the pilot before the mission and should be developed with the minimum chance of interference with the pilot's intent in other simultaneous tasks.

### 4.1.5 Cockpit Hardware and Weapons

#### 4.1.5.1 Windscreens and Canopies

Even though sensors may be available that will enable the pilot to *see* through the aircraft's structure, the pilot's preference will be direct visual sighting of targets and threats. The current approach is to seat the pilot high in a cockpit with a bubble canopy that has good visibility over the nose and sides. Such canopies, although in common use today, are not without limitations. As additional requirements are levied on the transparency system, such as signature reduction and compatibility with night-vision goggles, engineering compromises affect the canopy design. Part of the solution is to provide new transparency materials and new fabrication technology. Ultimately, however, the cockpit profile may be driven back to the aircraft contours and sensors used to replace the lost outward visibility. Because reliance on sensors must be increased to cope with expanded flight envelopes, the trend toward more agile aircraft may accelerate this change. High integrity and high fidelity in the sensor suite will be required to overcome pilot objections.

#### 4.1.5.2 Advanced Missiles

Modern radar-guided missiles incorporate high off-boresight capabilities as do many recent infrared-guided missiles. Launching a high off-boresight-angle missile presumes complex missile launch envelopes will be observed. Cuing with a helmet-mounted display can help the pilot launch within the multidimensional parameters of these envelopes. High accuracy in sensing helmet orientation and superb feedback to the pilot is required for high off-boresight-angle delivery of lethal weapons in a multi-aircraft environment.

#### 4.1.5.3 Displays and Data Transfer

A fundamental challenge to current cockpit technology is integrating the pilot as fully as possible into the machine through an efficient man/machine interface. Even with the pilot staring intently at an array of displays, the task is difficult. If the pilot is flying in a highly dynamic environment and is being challenged to maintain situational awareness by looking out of the cockpit, the difficulty of achieving high data rates across the man/machine interface is substantially increased. One approach is to use other senses in addition to the visual. A basic audio channel may use only words and tones to communicate information. A more sophisticated audio channel can include spatial dimension, pitch, and appropriate repetition to communicate more data with greater reliability.

Kinesthetic inputs through pressures on the pilot's extremities may provide an additional data channel. Such research must be cognizant of limitations in the pilot's ability to accept data at a high rate as previously discussed. Additional data channels may only increase the susceptibility to the loss of situational awareness.

#### 4.1.5.4 Controls

The data path to the pilot is only half the equation. The other half is the path the pilot uses to control and input data to the system. Simply controlling the flight path and the orientation of next generation aircraft may require control inputs beyond the stick, throttle, and rudder as currently mechanized. In fact, many modern aircraft already synthesize preselected blends of six-degree-of-freedom control using the pilot's four-degree-of-freedom controllers. For example, direct lift is used in flight control laws of several modern fighters.

Direct lift can be produced by deflecting trailing edge flaps or canards. This allows angle of attack and lift to be controlled independently, within aerodynamic, structural and control system limits. The benefits can be reduced drag, fuselage aiming to control gunfire, improved control response and better landing accuracy. Direct lift can be integrated into control laws so as not to require conscious control of vertical translation. To best exploit direct lift, control modes should be transparent to the pilot and not interfere with control of flight path or aircraft pointing. Aircraft with six-degree-of-freedom flight control are likely to also incorporate multimoding, with control laws modified depending on the task and the phase of flight.

The operation of complex sensor systems presents an additional challenge. The current approach is to provide the pilot with a large number of controls on the stick and throttle handles. This approach has been carried to its logical maximum. The real estate on the stick and throttle handles is largely spoken for, and many pilots today use only a few favorite and familiar functions. Taking full advantage of tomorrow's functionally agile systems will require new ways to manage those systems. One new approach is by voice command. Accuracy of voice-recognition systems is increasing, but high ambient noise and the effects of stress have, so far, restricted the utility of such systems in the fighter cockpit. Another limitation is the current requirement for the pilot to validate any voice entry before executing the system instructions. Very high reliability will be required before the validation step could be eliminated.

Eye trackers present another possibility as an improved pilot-interface device. If such systems can be refined to extremely high accuracy, simply looking at a control could be the same as actuating that control. Again, practical and safety considerations place very high standards on the accuracy of such a system. Current secondary systems often rely on the pilot selecting pages on cockpit displays using either buttons on the periphery of the displays or using touch-sensitive screens. Such displays require the pilot to look inside the cockpit with a possible loss of situational awareness. The displays are normally sequenced in some logical hierarchy. Design of the hierarchy must be so that any sequence of displays is intuitive and easy to back out of. Typical pilot concerns for this system are how do you get the display and how do you get out of it. The most effective solution seems to be a display sequence that follows a flight format rather than a subsystem

relationship. The uncertainty the designer must deal with is that the design mission seldom occurs. The pilot must have easy access to changes in sequence and content of displays. Given near-term data-storage capabilities, optional display sequences and formats which may be preselected by the individual pilot are possible.

#### 4.1.5.5 Egress Systems

When all else fails, agile aircraft make tougher demands on egress systems. Ejection at more extreme conditions is likely to result in injury. Two ends of the flight envelope need expansion today. At the high-speed end, the likelihood of supersonic ejection increases as the percentage of the mission spent at supersonic speed increases. Increasingly lethal weapons make speed less and less a sanctuary. The primary concern in high-speed ejection is wind blast leading to limb flailing. At medium and low speeds, trends in modern aircraft are to fly at higher angles of attack, higher yaw angles, and at higher body rates. Ejection from these conditions is more likely to result in aerodynamic instability of the seat and the crew member. Solutions currently proposed center on air-data and attitude-sensing systems on the seats and a control system to correct the seat's trajectory. The control system may control seat configuration, parachute, and drogue chute-release delays and aerodynamic or propulsive means of stabilizing the seat. A new ejection-seat test sled at Holloman AFB, New Mexico, has the capability of testing at high angle of attack and yaw as well as high angular rates. The engineering and test issue to be addressed is minimizing seat size and weight, while providing control capacity and pilot protection.

## 4.2 Pilot-Aiding and Weapon System Integration

### 4.2.1 Pilot-Aiding Requirements

To achieve full operational performance in today's aircraft, the pilot is required to perform several simultaneous functions:

- Fly the plane
- Maintain awareness of the total air battle scenario
- Communicate with other friendly forces
- Plan the optimum attack flying complex attack maneuver
- Control aiming and releasing multiple weapons
- Manage all onboard systems
- Organize self-defence against arriving threats
- Perform high-g escape maneuver for threat avoidance

All these tasks are very demanding and significantly increase the pilot's workload for operational success.

### 4.2.2 Weapon System Integration Concepts

Ultimately, there will always be unpredictable and variable human limitations to g tolerance, vertigo, and stimulation so that loss of situational awareness can result. The impact is that, while the boundaries of these phenomena can be pushed back, they cannot be eliminated and will remain at least somewhat unpredictable. Solutions must be developed that are designed into the aircraft, but that are nonintrusive in operation. The aware pilot must be able to continue to press mission limits; however, the pilot who has lost awareness must be protected. The ideal system for helping avoid loss of awareness would also protect against the consequences of loss of awareness.

Consequently, the need for a new onboard technology (computer-aided tactic), providing a full situation assessment and tactical decision assistance with automated optimum flight-path advice or automated attack and defense planning and execution, has been recognized. A fully integrated pilot-aiding system will involve several functional modules.

#### 4.2.2.1 Tactical Situation Assessment Module

The *tactical situation assessment* module requires complex algorithms that operate at the interface between the pilot and the onboard sensors and weapons to provide the pilot and the *attack management* function with the right information at the right time and to maintain a high level of situational awareness. The tactical situation assessment module addresses the following:

- Sensor Control
- Data Fusion
- Weapon Control
- Data Link

#### 4.2.2.2 Attack Management Module

The *attack management* module processes the tactics and provides trajectory guidance for the fighter during the engagement phase to achieve combat positional advantage.

When an aircraft in flight is opposed by superior numbers of enemy aircraft, the best engagement option may not be obvious and more than just situational awareness is required. The *attack management* algorithms determine flight trajectories to position the aircraft for maximum probability of target kill and maximum probability of own aircraft survival. The issues to be addressed include

- Navigation
- Attack Trajectory Evaluation
- Airframe Performance Maintaining
- Missile Avoidance/Evasion

#### 4.2.2.3 Pilot/Vehicle Interface Module

The pilot/vehicle interface module provides precise, concise, and complete information regarding the complex aerial engagement to the pilot, and provides the means by which he makes his decisions known to the system. Using this module, the crew can make quick decisions regarding system operation, including changing target priorities or deciding to execute the attack automatically, and selecting advised trajectories. These trajectories include

- Tactical Situation Data
- Weapon Employment Advice
- Threat Warning
- Recommended Flight Trajectories

Good integration of these functions will lead to a functional harmony between the pilot and the weapon system while increasing global effectiveness.

### 4.2.3 Tactical Processing Description

Figure 1 shows the main high-level functional block of an *Integrated Fire Control System*, or the *tactical processing* function. The *tactical processing* function performs the following:

- Tactical Situation Assessment
- Target and Threats Assessment
- Attack Management (Attack Planning and Attack Execution)

#### 4.2.3.1 Tactical Situation Assessment

The data from each of the different onboard sensors and from data link with friendly systems must be correlated and combined in the *data fusion process*, to provide as complete as possible a set of information for each object in the outside scene.

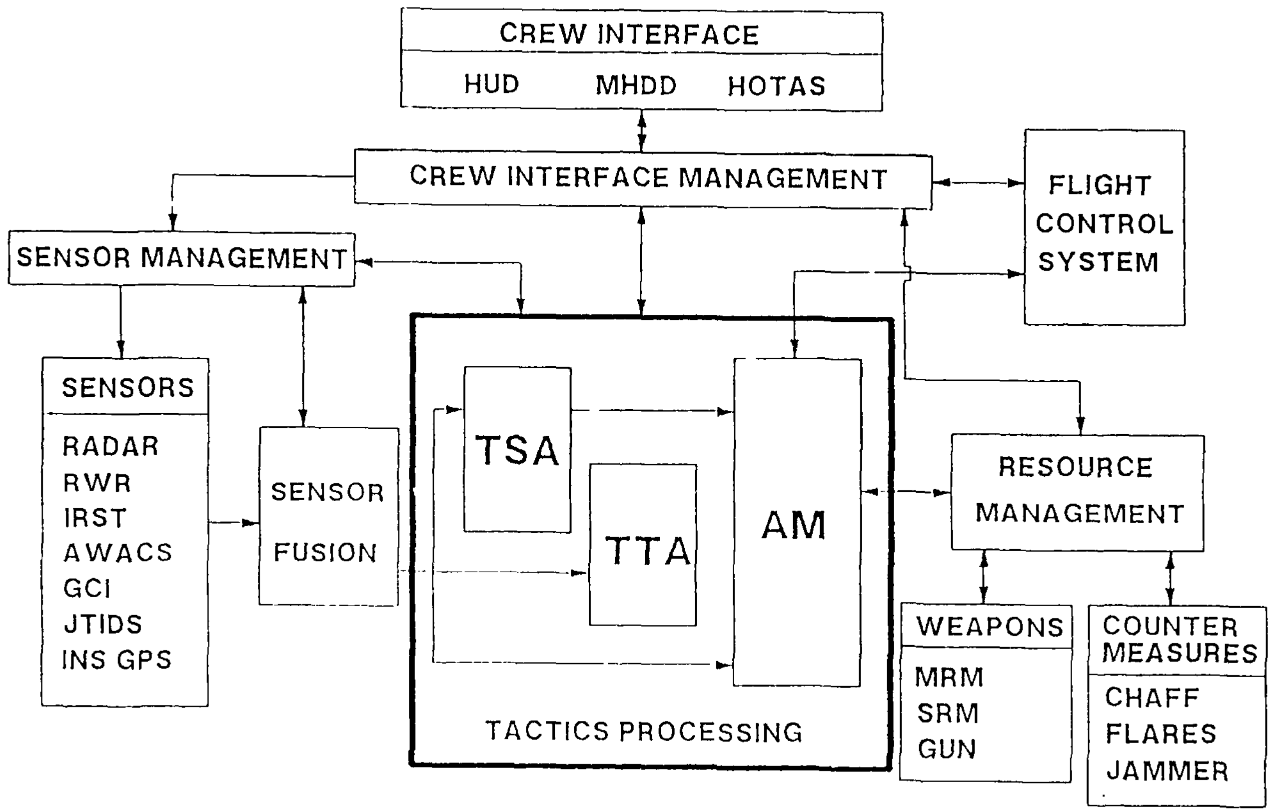



**Figure 4.1**
**IFFC General Structure**

The *tactical situation assessment* function processes the parameter of the *external-scene data base* to derive identity, intent, and grouping characteristics of the outside world objects.

Tactically, the identity assessment is the most important. It will not often change as a function of time, and consequently, represents a good basis for many long-term deductions. Friendly and neutral objects may be filtered out. Intent and grouping characteristics are likely to be substantially more dynamic.

#### 4.2.3.2 Targets and Threats Assessment

A *targets and threats assessment* function processes the *external-scene data base* and the outputs of the *tactical situation assessment* function. These functions are used to determine the outside world objects that are the most important targets and threats to be included in the more restricted scene provided to the pilot.

The relative strength of the own aircraft, or its formation against some enemy object or formation of the restricted scene, is evaluated by considering characteristic factors such as target quality, electronic counter measures capability, flight potential, and relative altitude. Once evaluated, the priority order for the targets and threats is generated.

When the number of targets and threats is reduced and the relative priority level is given, the *attack management* function can be initiated.

In case of a cooperative attack the *best* target chosen and the pilot s parameters are transmitted through the data link to the other friendly aircraft.

#### 4.2.3.3 Attack Management

The *attack management* function supports the pilot in both attack planning and execution. Planning includes target selection, trajectory management, and weapon selection. The main goals of the planned trajectory are

- Achieve a position of advantage in minimum time
- Achieve the position with minimum loss of energy
- Minimize the risk of exposure to threats
- Maximize the probability of success of the initial weapon firing
- Maneuver for a position of advantage against subsequent threats.

Good planning reduces the time to achieve the firing position, minimizes the loss of energy, minimizes the threats, and provides additional weapon-release opportunities against the target.

The *attack execution* involves flight guidance, if automatic, countermeasure operation, and weapon deployment.

Attack tactics are based on the advantages and capabilities of the sensors, countermeasures, weapons, and the data-processing system of the own aircraft. The attack rule is to launch weapons inside specified envelopes where the kill probability should be sufficiently high. Computation of such envelopes remains ambiguous because target maneuvers after missile launch cannot be accurately forecast. The concept of a "no escape zone", where any reasonable target maneuver will not negate the missile's kill probability, allows high probability missile launches but shrinks predicted launch envelopes and increases risk to the launching fighter. Designing a missile for an enlarged "no escape zone" with minimum shrinkage to the aircraft's missile launch envelope is an excellent example of design optimization at the system level.

The functional description of the *attack management* function is illustrated in Figure 2. Operational modes include *defence, immediate attack, long-term attack, and target selection*

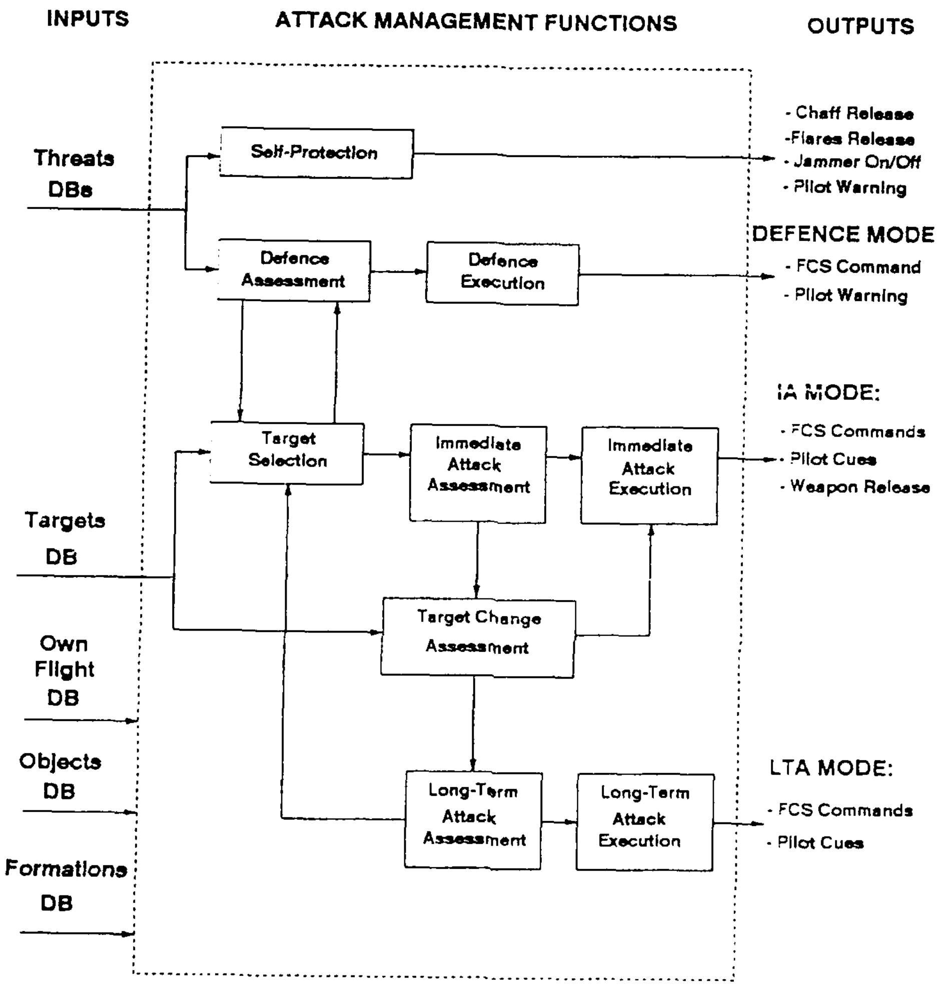



Figure 4.2
Attack Management Functions

#### 4.2.3.3.1 The Defence Mode

The *self-protection* function provides the evasion of an immediate threat or enemy radar lock-on. Since hostile missile launches are usually undetected, an on board simulation that computes a missile "no escape zone" for the enemy system and displays results to the pilot can keep him aware of his own possible no risk and low risk launch zones. Once inside the enemy launch zone or even the enemy "no escape zone", such a system provides the pilot with the following outputs:

- Chaff Release Command
- Flares Release Command
- IR Signature Control Command
- Jammer On/Off Command

These signals or outputs depend on the inputs from the *threat data base*. This data base considers various types of threats such as missile avoidance, gunnery avoidance, zero time threats. After the various types of threats are considered, an appropriate countermeasure is provided.

The *defence assessment* function determines whether or not the total response should be defensive. A positive conclusion can be made if an immediate threat, with an high risk to the own aircraft, is in approach (collision, gunnery or missile avoidance) or there are aircraft threats and no target can be attacked.

A positive answer of the *defence assessment* function leads to the defense execution. The *defence execution* function provides a warning to the pilot, highlighting the kind of threat, and flight-guidance commands to the flight-control system or to the pilot as a flight director to avoid the threat.

Missile-avoidance maneuvering, for example, should be very prompt and well coordinated with the self-protection actions. The avoidance maneuvers are defined as actions early in the missile time of flight. Controlling the angle between the line of sight (LOS) from missile and aircraft flight path, the system flies the aircraft to a safe position beyond the missile flight envelope. Endgame maneuvers are performed to create a safe miss distance when avoidance is not possible and to coordinate the use of available countermeasures to provide greater miss distance.

The aircraft threat avoidance is selected in the event a threat aircraft exists and no attack is feasible. It is required that the LOS vector to the threat aircraft be inside the *missile approach warning* detection angular envelope to be ready to respond to enemy missiles in time and effectively. The function computes a vector denoted as *weighted average direction to the highest priority threats* and provides the pilot with an advised flight path. Displays include the LOSs to the threats and the *missile approach warning* angular envelope to assist the pilot in determining safe maneuvering boundaries for flying the aircraft.

#### 4.2.3.3.2 The Immediate Attack Mode

If the *defense assessment* function gives a negative answer and a target is selected, an immediate attack is considered feasible. The *immediate attack assessment* function performs the following tasks:

- Target trajectory prediction for a subsequent defined time
- Attacker trajectory prediction for the same time
- Weapon release possibility assessment

If a positive answer is given to the *immediate attack assessment* function, (high probability to hit the target and low risk of being shot down) the *immediate attack planning* is executed. If a negative answer is given, the *long-term attack* function develops a new plan and assessment computation.

The *target trajectory* sub-function predicts the target trajectory for a subsequent defined time, assuming a constant target maneuver (acceleration, velocity, etc). In contrast, the *attacker trajectory* sub-function prediction assumes that a recommended trajectory from the current state is used. The *weapon-release* assessment checks offensive weapon envelopes of all available weapons types at computed trajectory points.

A positive assessment answer is produced when the predicted target location is found to be inside the predicted high kill probability envelope of any of the available weapons. If more than one weapon can be used, a priority order is developed and presented for pilot selection.

The *immediate attack execution* function performs the flight-guidance and fire-control computations. Flight guidance brings the attacker to the weapon-release position and fire control produces the weapon-release recommendation for the pilot.

#### 4.2.3.3.3 The Long-Term Attack Mode

The *long-term assessment* function operates when the *immediate attack assessment* function yields a negative response. The purpose is to bring the fighter to a point where the *immediate attack* becomes possible. This function performs computations concerning the already selected target and it operates differently for *before release* and *after release* cases. In the first case, no own missile is in the air and the function proceeds to weapon release. A trajectory is computed and planned and if it results in a negative conclusion (either the weapon release is impossible or the trajectory unsafe) the attack is aborted and another target selected. In the second case, some own-released missile is still in the air and the own aircraft may be required to keep the target inside the radar envelope for some time after release. The own aircraft must maintain a position to release another weapon in the shortest period of time against the same target if the first missile misses it.

The *long-term attack execution* function performs, through the aircraft flight-control system, the planned trajectory to eventually bring the aircraft to the point where the *immediate attack* maneuver becomes possible.

Different types of trajectories, already computed by the *long-term attack* assessment, are considered. These trajectories are

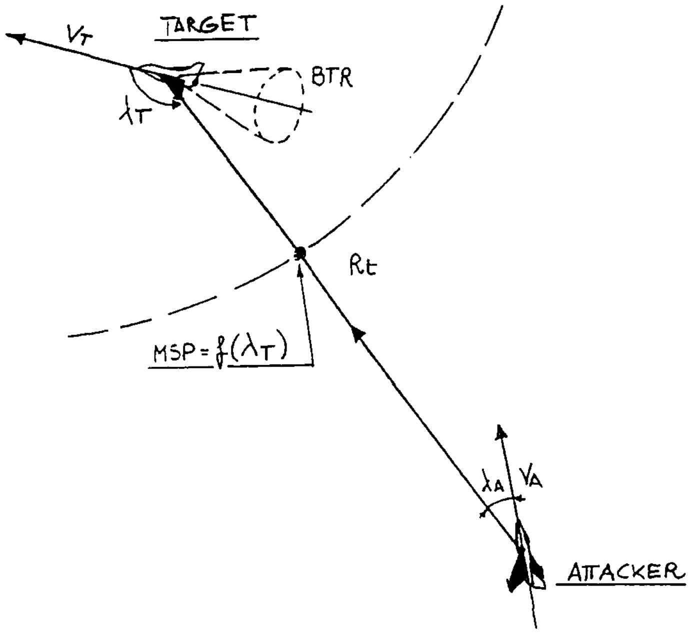
- Target Tracking
- Collision Course
- Backward Region Approach

Generally, for large distances, the attacker maintains a flight path with a straight-line trajectory to target intercept. Beyond a defined range to the target, the attacker flies this straight *collision course* provided that the target does not maneuver. For a maneuvering target, the collision course is replaced by a trajectory to the target's turning circle. The *backward region approach* trajectory is used only when the range to the target is below the *maneuvering switch point* range, depending on the target aspect angle. This last trajectory is the minimal flight-path time that brings the fighter to some point behind the target (a cone with a certain angle and vertex in the target center of gravity), that is, a region from which the weapon-release task execution is most convenient for the attacker or an *immediate attack* with gunnery mode is feasible. Figure 3 illustrates some of the above mentioned parameters.

#### 4.2.3.3.4 The Target Selection Mode

The target selection is performed when there are targets in the area and no target has been yet selected, the attacked target has been hit, or the attack against the selected target becomes not feasible. For every checked target, the attack trajectories are planned and evaluated in their priority order until some plan is approved by the system. In this type of evaluation, the possible releases of the available weapons are checked and the highest priority *releasable weapon* is selected as a part of the approved plan. The attack plan evaluation involves the assessment that no enemy aircraft would become possible threats on the predicted trajectory, of course assuming some constraints on the motion and intercept trajectories of the enemy attacker.

A target change will occur if the attack becomes no longer feasible, some enemy aircraft threatens the own aircraft, the enemy aircraft needs to be attacked immediately, some higher priority target can be attacked immediately, or in case of a cooperative attack, if some friendly fighter is already attacking the same target.




$\lambda_A$ = Attacker Aspect Angle
$\lambda_T$ = Target Aspect Angle
$V_A$ = Attacker Velocity Vector
$V_T$ = Target Velocity Vector
Rt = Line of Sight (LOS) Vector

**Figure 4.3**
**Attack Parameters**

#### 4.2.4 General Flight Control System Requirement

Automatic flight guidance can be generally selected for long-term attack, where the planned trajectories do not require high maneuvering, and for defence execution where very prompt and well-coordinated maneuvers are required. However, in-close combat, the automatic guidance can perform very high-g maneuvers that could easily lead to pilot disorientation. In this case, flight director information is given to the pilot to help him follow the planned flight trajectory.

To insure carefree maneuvering during attack execution, but particularly during weapons avoidance with automatic flight guidance engaged, a flight-control system with the *Carefree Handling Function* is absolutely necessary. This type of system ensures protection against

- Control loss
- Excessive control power demand
- Excessive structural stress
- Undesirable effect on engines
- Undesirable effects on pilot stamina

### 4.3 Conclusion

#### 4.3.1 Physiology

Modern fighters take advantage of advanced aerodynamics and control technology to achieve exceptional maneuvering performance. Advances in sensors and data processing present the pilot with more information to absorb, sort, and act on. Exploitation of these capabilities exposes the pilot to physiologically demanding maneuvers and simultaneous mental demands. New technologies can provide physiological protection and assist in data management and interpretation. Properly designed controls and displays can enable the pilot to extract maximum performance from his system and achieve unprecedented combat capability.

#### 4.3.2 Pilot-aiding and Weapon System Integration

For a fighter aircraft today, the achievement of significant technology advancements in system automation and *computer-aided tactics* enables the complete, functional sensor integration (own or external), fire control, flight control, weapons, and interfaces with the pilot. These technological advancements lead to an effective, improved beyond-visual range, multiple target attack capability with an excellent transition to close-in combat that significantly increases the probability of survival and the success of the mission.

Controlling and reducing the pilot's workload is the intent of previously discussed systems. These systems must prioritize tasks into a hierarchy and still allow the pilot to work at the level he chooses. Those tasks below the level of the pilot's attention may be undertaken by a system that relies on a preselected set of rules to accomplish these actions. Such systems may rely on data links to allow augmentation of a pilot's decision-making capability using remote assistants. Selecting the hierarchy and determining the pilot's operating level may become part of the pilot's preflight planning.

### 4.4 Summary

In summary, agility introduces a vast array of new requirements and performance standards for cockpit design. Making full use of the capabilities of the total weapons system requires excellence in the pilot's integration with the system and requires several current limitations to be overcome.

## 4.5 Recommendations

Research into the physiological effect of high angular and linear rates and accelerations under various conditions of visual reference is needed.

Additional physiological research needs to be conducted to determine whether high-g, below the level causing loss of consciousness, contributes to loss of situational awareness.

A more sophisticated audio channel can include spatial dimension, pitch, and appropriate repetition to communicate more data with greater reliability. Such research must be cognizant of limitations in the pilot's ability to accept data without becoming saturated.

Pilot aiding approaches, algorithms and system hierarchies must be designed to interact with the pilot in a natural manner. The systems must, at a minimum, protect the pilot when he cannot provide control and should augment the pilot in high workload phases of flight.

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# Chapter 5: Evaluation

## 5.1: Introduction

Test and evaluation is an exacting process for even simple designs and articles. The term test is worthy of some discussion, before we turn to evaluation. The definition contained in 'The Glossary: Defense Acquisition Acronyms and Terms', prepared by the Defense Systems Management College, is as follows:-

> *A "test" is any programme or procedure which is designed to obtain, verify, or provide data for the evaluation of: research and development; progress in accomplishing development objectives; or performance and operational capability of systems, subsystems, components and equipment items.*

***It is evaluation which transforms test results into useful information.***

In this, the final chapter of the report, the intention is to examine evaluation of a system for which Operational Agility is a requirement, either specified or inherently implied by the overall Weapon System requirements. As interpreted by the Working Group, evaluation forms an essential element of the continuous iterative process that must be followed when designing a vehicle to be operationally agile.

Evaluation has to start at the conceptual outset of the design phase and continues through all stages of the design development, conventional test, including flight test, production and service evaluation and development. This is in consonance with involvement of the customer in the early stages of development that characterise concurrent engineering.

As noted earlier in Chapter 2, Section 2.4 on Airframe Design, agility is essentially designed in from the outset and it is rare that it is possible to augment the levels of agility that are achievable in the design. Typically, such amendments are most commonly possible only in the systems or weapon fit, where the improvement is part of a major upgrade at some stage in the vehicle's life. Enhancing levels of airframe agility may form part of this process but would normally require extensive rework of the airframe.

Evaluation needs to start early in the design process as part of the assurance that the design continues to meet the specification. Indeed, the specification should not be finalised at a detailed engineering level without giving thought as to how the vehicle or system is to be evaluated or to what function the vehicle will be put in its Service life.

Evaluation of Operational Agility must focus in its contribution to the design balance as illustrated in figure 1.2 of Chapter 1. This contribution may be measured quantitatively through the metrics described throughout this study as well as the expert qualitative judgements of test crews. It is imperative that the procurement agency, as well as the manufacturer, understand the relative weight of agility with respect to the other fighting qualities. The most unambiguous method of quantifying agility is with the time required to perform the mission tasks. This metric would be expected to form the basis of the specification that must be verified. Using the time-line concept presented thoughout this report, the time delay of each design component for each specific mission task can be accurately measured.

What is unclear at this time, unfortunately, is the operational importance of the numerous specific agility metrics. Since agility is a fighting quality, the evaluation team must include designers, experimenters and operational crews. Since these professions are rarely embodied in one individual, team work will be essential. This team must have a clearly defined set of objectives that can be achieved within both time and money constarints. This is perhaps the most challenging aspect of agility evaluation.

## 5.2: Evaluation Techniques

Chapter 2, Section 2.2 describes in detail the metrics which have been proposed by a number of authors and develops a framework into which the metrics logically fit. It is suggested that this framework is applicable to any system associated with the the flight vehicle under consideration. The key to this framework is that it involves a gradual build up in complexity of the metrics, until finally the system is evaluated as a part of the total airborne system.

It follows that in order to evaluate Operational Agility, a build up technique is adopted which measures each individual characteristic which is of significance, then sets about measuring the combinations which are appropriate to the task in hand. This follows the methodology of the metrics, which progress from transient, experimental metrics to those which measure mission task elements.

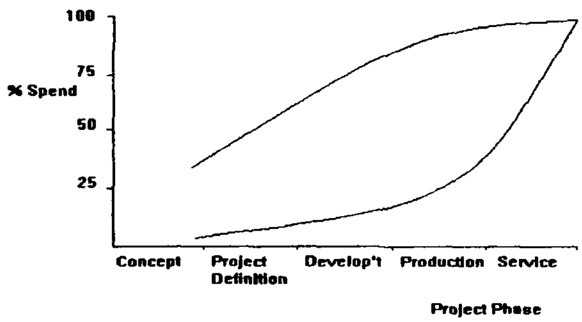
### 5.2.1: Methodology

The overall framework by which Operational Agility, or its contributing aspects, is evaluated is provided by the recommended framework, which has been evolved from Chapter 2, Section 2.2. However, for any individual project, the specific evaluation metrics which will be used to ensure that the Operational Agility of a design is maximised, should be decided at the beginning of the design cycle, as they are clearly demonstrable to be a function of the role that the vehicle is designed to fulfil. Recognition of this allows the same methodology to be applied to any category of vehicle, in much the same way as Handling Quality specifications can be used for military combat aircraft or transports, etc.

The methods which will be used will cover analytical design methods, simulation, flight test, operational evaluation and life cycle development aspects. The key to being able to evaluate successfully is to consider the evaluation process before the engineering detail specification process is started. In this way, it is possible to take account of the function and the means by which this will be demonstrated and evaluated in the specification process. After all, every system on the aircraft has a purpose and a way of demonstrating that the purpose is being fulfilled.

Each phase of the design and development activity will of necessity be iterative or cyclical in nature, with differing levels of analysis being appropriate as the design develops, and must be associated with some way of confirming whether or not the procedures in use are generating the desired output or conclusion.

**Figure 5.1: Total Life Cycle Costs, Committed v Actual**




A clear message, that results from the recognition of the nature of this process, is that the cost associated with getting the basis for the design to a satisfactory state before going to detail design is well worth incurring, as it will almost always result in saving costs at a later stage in the life cycle of the system under development. Figure 5.1 illustrates this concept.

Rapid prototyping schemes are a direct recognition of this situation and, hence, they can be regarded as an agility enabler.

As this evaluation methodology involves the customer at a very early stage of the development, then this process is no longer associated with the traditional Quality Assurance activity which used to occur.

### 5.2.2: Techniques

#### 5.2.2.1: Introduction

In deciding upon the techniques which are to be used in evaluation of Operational Agility it is worth recalling the definitions associated with the subject:-

> ***Operational Agility* - *the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.***
>
> ***Transient Agility*** is a continuously defined property reflecting the instantaneous state of the system under consideration.
>
> ***Airframe Agility*** - the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path or pointing axis and to its ease of completing that change.
>
> ***Systems Agility*** - the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.
>
> ***Weapons Agility*** - the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures.

From these definitions, the necessary techniques become evident. The metrics that will be used reflect the transient, experimental and operational elements, as described in Chapter 2.2 and 2.5 which dealt primarily with airframe agility metrics. However, this form of assessment, as has been shown in Chapter 3 and Chapter 4, can be used to evaluate any aircraft system, of which the airframe is merely one.

Typically, the generalised framework for the evaluation process to be applied will look similar to that of Table 5.1. This indicates the increasing level of complexity that the evaluation process must undergo as the development programme proceeds, but it is also clear that there are possible ways of evaluating the relative worth of the differing contributing systems prior to undertaking detail design work. Such methodologies are essential for establishing the appropriate design balance for the system or systems in question, including the airframe.

A crucial aspect of the evaluation methodology is the mission task element concept. In the early stages of design, even at the conceptual stage, this technique can be used to determine what is required to perform any task and allows a study of all of the design options available such that the most effective way of achieving the task results. Mission task elements are already part of the methodology in use for rotary wing vehicles, but the fixed wing community can and should use this to advantage. Moves to adopt this methodology are already in hand.

With such concepts in mind, it is then relatively simple to define the experiments and the test methods which can be used to confirm that the design is conforming to both expectations and requirements at any stage of the development cycle.

These studies will include analytical design studies, non-real time, real time simulation studies, particularly when there is a need to integrate one or more elements via a piloted assessment, culminating with flight evaluations involving initially clinical flight test or test manoeuvres and moving on to operational assessments.

The methods available range from the very simple to the very complex and build up from simple elements to the total system simulation or flight test. Indeed, for some very complex systems, simulations might be the only feasible method of performing the evaluations, even if the simulations have to be based on information gained from individual, simpler flight test experiments relating to parts of the overall system. Indeed, such a concept formed the basis for the proposals to evaluate the SDI systems, as noted in reference 2.

**5.2.2.2: Airframe Agility Test Techniques**

Section 2.5 discussed numerous simulation, simulator and experimental flight test efforts which establish the current airframe agility test techniques. At the present time, all of these techniques possess limitations.

Simulations generally do not model accurately higher order dynamics. These dynamics dominate the instantaneous time regime. Longer term motions are less sensitive to this effect and therefore can be better modelled. Simualtions may therefore be of more use for airframe for airframe operational agility assessments.

Simulators possess the same model limitation but in addition motion and visual requirements for the closed loop system are demanding. Currently, simulators do not provide adequate visual and motion cue fidelity for large amplitude motions. The simulator has proven to be beneficial for practice prior to gathering experimental metric information during costly flight tests. As such, the simulator does not currently appear to be a source of airframe agility data.

Experimental flight testing reveals the higher order dynamics results but is limited by a vague understanding of the operationally significant characteristics. With the high cost of flight time, especially with highly instrumented test aircraft that possess advanced technologies, flight test techniques have been slow to progress. Experimental aircraft seem to be the primary source for transient and experimental agility data. To be fully understood, agility as a design objective will require a great deal more experimental flight testing. This luxury was available to develop performance and flying qualities concepts.

The development of airframe agility test techniques appears to be limited by understanding of higher order dynamics, simulation fidelity and the cost of conducting experimental flight test to build up a valid database.

**5.2.2.3: Systems Agility Test Techniques**

Systems agility test techniques are essentially non-existant at this time as a stand alone area of investigation. As was discussed in Chapter 3, Section 3.4, rapid proto-typing techniques are effective for investigating the pilot-vehicle interface associated with systems control and its impact on the time to carry out operator functions. Other techniques involve avionics integration facilities and anechoic chamber facilities. All these techniques provide information that is applicable to measuring the agility of systems.

As discussed in Chapter3, Section 3.4, some test facilities have the capability to simulate the electromagnetic combat environment with anechoic chambers, threat emitters and the test aircraft. These facilities do integrate weapon simulations as well as fixed base flight simulations. For a realistic Operational Agility evaluation, all these capabilities must be integrated into a total package that permits a pilot and crew to exercise the Total System in realtime against realistic threats. This capability would be expensive but still much cheaper, easier to control and easier to repeat then flight testing.

**5.2.2.4: Integrated Aircraft Operational Agility Test Techniques**

Weapons agility testing is perhaps best conducted during the test of the integrated aircraft and weapon systems. The weapon itself is rarely used by itself and as such relies on the aircraft, systems and the integration for it to be used effectively.

Flight testing weapons is the most expensive of all the techniques and therefore produces the smallest sample size of data from which to base an agility assessment. The concerns that were raised in Chapter 3, Section 3.1 for the mismatch between current weapons and advances in aircraft technologies must be a prime concern for developing future test techniques. What will be required is a sound selection of an affordable number of critical test cases for verification. The test method will be the same as for any weapons test. The conditions though will have to emphasise dynamic combat situations characteristic of rapid nose pointing and quick shots. Unfortunately, this approach may be risky because of the potential for failure and therefore wasted cost.

One method for overcoming this constraint may be with ACMR/I integrated with flight test instrumentation and accurate weapon simulations. ACMI generally provides coarse flight mechanics information. If the test aircraft was capable of receiving both the ACMI and flight test instrumentation a better picture of multiple aircraft manoeuvring may be obtained. Now, if combined with an accurate weapons simulation under rapid nose pointing could be

developed, it is possible that significant cost savings could be achieved as well as providing much more operationally significant data.

**5.2.2.5: Simulation of Agility**

Since the simulator will likely be relied on heavily for pilot training for flying, systems and combat tasks, it will be exepected to closely match the actual aircraft. This will place heavy demands on the agility characterisation process and especially airframe agility. As mentioned previously, simulator fidelity is currently limited. Advanced techniques such as virtual reality may assist in overcoming this limitation.

One concept, which has already seen limited use for very specific purposes, is the use of onboard simulation of various threats to stimulate the systems under test. Examples of this have been set up for simulating tracking tasks where the test vehicle is flown against a synthetically generated target displayed on the head up display but the concept can be used for any of the onboard systems, especially where a complicated trial involving other aircraft or ground stations is required.

As an example, the USAF STandard Evaluation Manoeuvre Set has established a method for use in evaluation of airframes in order to establish the airframe agility. Similar concepts are used elsewhere but, as yet, primarily for assessing the airframe and its handling or performance.

This type of concept requires extension to the other systems and the total Weapon System. The framework which is proposed in this report might allow this to be achieved as it should be sufficiently general, being formulated around the mission task elements and transient and experimental agilty metrics.

**5.3: Data Acquisition**

Operational agility drives the need for time based data on all the aircraft systems. Currently, data tends to be available from dedicated onboard flight test instrumentation, from structural use monitoring systems or possibly from accident data recorders. With the exception of flight test aircraft instumented specifically for this sort of task, data tends to be somewhat specific and limited as to its possible use, especially with regard to aircraft flown in normal squadron service. Another alternative would be to make use of data recorded on ACMI ranges, although this information is not available to design organisations, unless by specific agreement.

In order to understand and quantify the Operational Agility of a Weapon System, there is a need to gather data on all the systems simultaneously, in order to determine the actual usage that is being made of all the systems at any time. Additionally, there is a need to record data under realistic operating conditions, including combat use and even actual war.

As an example, after the Gulf War, DARPA reconstituted a ground engagement using data derived from extensive on-site surveys and interviews with participants. The objective was to develop a simulation which would allow for the assessment of alternate tactics to those actually used in the battle.

Modern fighter aircraft are equipped with one or more data busses to support flight control functions as well as avionics integration, display and data fusion. The contents of these data busses has been designed from the bottom up to support these functions. While data from these busses has been used in flight test to support other functions, the format and nature of the data is not always totally supportive of other functions. Some of the data on the bus, for example, will have been held in buffer for an unknown period of time.

If the data on the aircraft data-busses were captured and accumulated into a database, such data could support analysis and simulation. To make this happen would involve:-

A top down restructuring of data on aircraft busses to support the multiple users.

Data storage to preserve bus traffic for later use.

Development of data archiving technology to allow preservation of large amounts of flight data.

Development of data basing and access techniques to support multiple users and large data banks.

Standardisation of formats for simulation and analysis to match on-board data formats.

Integration of off-board data sources with on-board derived data. This would, for example, allow AWACS data or ACMR data to be integrated with data from an individual aircraft.

The capability exists now to gather the information and to handle the database that results. The community has yet to use the information in any other than a piecemeal manner. The implication is that the data acquistion would need to be structured with all the potential users in mind and should be sufficiently flexible to accommodate changing and growing needs.

The above concept is of particular interest to the agility community for two reasons. From a flight mechanics point of view, there is an absence of data on actual usage of aircraft. Many tacticians consider high angular rates and high angles of attack to be of little importance, given the characteristics of current missiles, yet evidence from structural monitoring systems on airframes indicates that pilots make extensive use of high angles of attack in flight. This anomaly could be addressed by the data described. From an operational agility viewpoint, it is important to be able to compare operating demands as made by pilots and executed by airframes, avionics systems and weapons.

Data derived from this approach would increase the accuracy of OT&E force level tests and provide the ultimate validation for such tests. Combined with simulation, these data will allow extension of test scope beyond current systems.

The most critical measurement in agility test is time. It is imperative that the time measurement possess adequate rsolution, probably of the order of milliseconds. Tests with multiple time sources must be synchronised. Most test facilities are converting to the world wide coverage time code feature of the Global Positioning System (GPS) constellation of satellites.

Airframe agility parameters are essentially based on well established flight mechanics parameters. As such, existing instrumentation is more than adequate to measure parameters from which transient, experimental and operational agility metrics would be calculated. The best experience to date was the AFFTC effort reported by Lawless. The key lessons were:-

$N_{zdot}$ was selected as representing a class of several other proposed metrics because it is familiar to pilots and engineers.

Pitch acceleration was chosen over angle of attack because it is easily derived from available instrumentation - this relates back to the need to use all the available sources to maximum effect.

Maximum instantaneous roll acceleration was selected for manoeuvres of up to 360 degrees again because of familiarity.

Torsional agility was not used as it was too sensitive to measurement outputs.

The pilots involvement is more important in the early phases of decision making than before. This arises because most of the mechanical systems are being replaced by software controlled functions. His ability to interface correctly and efficiently with these functions will dictate the effectiveness of the vehicle. Again, this leads back to the importance of Rapid Prototyping.

Systems and weapons agility parameters are available on the aircraft's data bus(es). Technologies are now available to record all the message traffic on the bus in real time for post flight analysis.

The PVI is difficult to measure because of the human operator. HUD and over-the-shoulder video recorders can record most of the information displayed to the pilot and what pilot reactions were applied.

## 5.4: Conclusions and Recommendations

Evaluation forms a key to ensuring that the Operational Agility and vehicle effectiveness are maximised from the ouset of the design process. Properly used at the early conceptual stages of design, it has a major role to play in determining where scarce research and development funds are best spent to ensure that the correct design balance results.

There is a need to gather data under all operational conditions including actual combat. This will build, for any aircraft, an operational agility database which will enable better specification of the characteristics needed for future variants and new aircraft designs. Given the broad definition of Operational Agility, such a database would be of vital interest to the many related disciplines involved in the design, development and evaluation processes.

To achieve this requires the co-operation of technology and operational groups so that issues like the content, format and protocol of the data , the storage media and acquisition would be defined. It is recommended that the AGARD Flight Mechanics panel, taking advantage of its role within AGARD with respect to systems integration, should establish a further working group tasked with examining the issue of establishing and utilising such a data base. Such a Working Group would include specialists from technology, operations and data information backgrounds.

## References:

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**Table 5.1: Evaluation Framework - Methods and Techniques**

| Agility Constituent | Open Loop Measures | Closed Loop Measures | Part Mission Tests | OT&E Whole Mission Tests | OT&E Force Level Tests |
|---|---|---|---|---|---|
| | Component Tests | Whole Subsystem Tests | Limited Scope, whole System Tests<br><br>(One M.T.E.) | Limited to one Aircraft and one type of Mission | Multi-Aircraft, Multi-Mission evaluations |
| Systems | Bench/Lab tests<br><br>Sensor Performance | Test Range evaluations.<br><br>Sensor Displays | Whole system behaviour, stress the inter-relationship of all constituent parts | Behaviours of many like systems in realistic environments | Behaviour of systems in concert with other battlefield systems |
| Weapons | Lab tests, fusing, warhead effectiveness | Range tests | Whole system behaviour, but with limited tests scope | Whole system behaviour, with broad test scope | Weapon remotely targeted |
| Airframe | Transient tests<br><br>Individual axis properties<br><br>Signature | Steady performance tests<br><br>Multi-axis blended tasks<br><br>Susceptability | Navigation Accuracy, Targeting, Weapon separation and accuracy, threat detection and classification | Fly navigation route, engage and deliver weapon or cargo Avoid or evade individual threats. | Operate as part of multi-element force in a multi-threat environment. |
| Pilot-Vehicle interface | Sub-task behaviour, Laboratory mock-ups, Hardware demonstrations | Part-task measures, Dynamic Single Element Display, Simulations | Part task simulations in ground or flight based simulator or in engineering prototype cockpit. | Flight or ground based tests in fully realised cockpit of simulator or actual test aircraft. Assessment of aircrew task loading essential | Flight or ground based tests in aircraft or simulator with dynamic data supplied from off-board sources. Reassess aircrew task loading. |
| Number of tests, cost and complexity | Many simple, low cost tests early in development cycle | Much fewer tests | Fewer yet, done in varied environments | Few enough to need to rely on Operations Analysis to interpret and extrapolate | Might be done by Operations Analysis alone |

**Table 5.1:** **Evaluation Framework - Methods and Techniques**

| Agility Constituent | Open Loop Measures | Closed Loop Measures | Part Mission Tests | OT&E Whole Mission Tests | OT&E Force Level Tests |
|---|---|---|---|---|---|
| Remarks | This open loop test area examines basic physical properties and helps the design team measure the success early on. The results are used to feed analysis and simulation. | These tests of subsystem properties begin to establish the measured outputs of the subsystem in a fixed, artificial environment. | These tests examine the behaviour of the whole system, in a controlled short term setting, for the first time. Many of these tests can be strung together for a study of the mission. This area is ripe for piloted simulation. | These tests probe for fitness and robustness in varied environments and against varied threats. | These tests may be performed solely by operations Analysis based upon the results of the lower level tests already conducted. |

## Chapter 6: Conclusions

### 6.1: General Conclusions:

The Group has completed its study of Operational Agility with this report. In undertaking the study, a greater understanding has been reached of those subjects which influence Operational Agility and how these subjects, via the use of Operational Agility concepts, may be related to the combat effectiveness of the Weapon Systems. In reaching this understanding, the Group has proposed definitions of the agility terminology which should prove universally acceptable, viz:-

> ***Operational Agility*** is defined as ***the ability to adapt and respond, rapidly and precisely, with safety and poise, to maximise mission effectiveness.***
>
> ***Transient Agility*** is a continuously defined property reflecting the instantaneous state of the system under consideration.
>
> ***Airframe Agility*** - the physical properties of the aircraft which relate to its ability to change, rapidly and precisely its flight path vector or pointing axis and to its ease of completing that change.
>
> ***Systems Agility*** - the ability to rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness and his ability to direct and launch weapons in response to and to alter the environment in which he is operating.
>
> ***Weapons Agility*** - the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures.

To go with these definitions, the Group has arrived at a methodology for assessment of the various component systems which contribute to the Operational Agility or combat effectiveness of a Weapon System. This methodology is described initially in Chapter 2.2, where it has been derived from consideration of the Airframe Flight Mechanics. However, it has been suggested, with some evidence to support the assertion, that the framework will also apply to any system which contributes to the Operational Agility. Further, it allows the relative worth of the differing systems to be evaluated against each other.

This represents the first major conclusion of the Working Group, particularly as on further examination, *it would appear that the methodology could be used for any class of flight vehicle, although the values of the metrics would need to change appropriately.*

The parallel with Flying Qualities criteria as applied to different classes of aircraft is striking, although this was not intentional.

### 6.2: Specific Conclusions:

Whilst each section and chapter of the report draws its own conclusions, there are some further major conclusions which deserve to be drawn out and discussed in detail. These conclusions are presented here, viz:-

**1) There is a mismatch between the Weapons and the Airframe capabilities.**

A great deal of effort has been expended in developing the airframes to be highly agile but this has not necessarily been matched by the equivalent development of the weapons that the airframes carry. This does not imply that there has been no activity, there has, but there needs to be a concurrency in the development if the total effectiveness is to be maximised. The Working Group believes that this warrants a symposium to illustrate current problems and identify the way these can be solved by Operational Aglity methodology.

**2) The way in which aircraft and their associated systems are specified is in need of review and revision.**

Current combat aircraft specifications and requirements are not really appropriate for the complex, integrated vehicles which have to result from attempting to meet the requirements. The very complexity of the vehicles often means that decisions relating to the design options may not take into account all the influences, leading to engineering difficulties and expense later in the processes of development and procurement.

The concepts involved in Operational Agility can assist in the process of determining what the specification and requirements should contain and in the design and subsequent evaluation of the vehicle that results.The object should be to define the function and purpose, then establish the methodology and means of evaluation prior to issue of detail engineering design specifications. To achieve this, there needs to be close interface and teaming between the customer, end user and possible designers and suppliers of equipment, airframes, etc.

3) **The achievement of a cost effective design balance and the maximisation of Weapon System combat effectiveness are central to the concepts of Operational Agility.**

This relates to the problems of vocabulary which has inhibited communication in this field. However, this report should assist by providing the necessary definitions of agility terminology by which the communication can be established. The key is to recognise the broad scope that Operational Agility encompasses, and to be specific about which aspect or system is being discussed.

To achieve the design balance not only needs the definitions of agility, it also requires standardised agility figures of merit, together with a proven quantification methodology applicable from concept through design, test and into operational contexts. The role for the vehicle will give rise to differing weighting factors for the agility attributes, influencing the design balance.

The proposed metrics structure seems to logically characterise the airframe agility, ie. transient, experimental and operational. However, there is insufficient data at present to clearly determine the tactical meaning of airframe agility metric results.

The Operational Agility structure is applicable to mission oriented and weapons agility.

4) **There is a need for Global data acquistion.**

In order to understand and quantify the Operational Agility of a Weapon System, there is a need to gather data on all the systems simultaneously, in order to determine the actual usage that is being made of all the systems at any time. Additionally, there is a need to record data under realistic operating conditions, including combat use and even actual war. The capability exists now to gather the information and to handle the database that results. The implication is that the data acquistion would need to be structured with all the potential users in mind and should be sufficiently flexible to accommodate changing and growing needs.

The Working Group consider that this could be a subject for a new working group which should involve members of the operational community, design organisations and technical information specialists with view to arriving at a mega-database usable by any technologist or operational person for their purposes by employing appropriate interrogation techniques.

5) ***Combat success requires more that an agile airframe.***

Use of the proposed Operational Agility methodology should enable the crucial aspects of each contributing system to be identified. The object will be to focus on the time delay of each aircraft subsystem with the aim of reducing the delays without over-emphasis on a specfic system aspect which could potentially lead to increases in time delays by other components, including the pilot.

Clear understanding the time delays for mission functions enables identification of actions to automate, ie housekeeping, leaving the crews limited attention time to more critical tasks such as the tactical situation. This relates to conclusion 8, regarding the use of rapid prototyping.

6) **Quickness parameters provide best means to bound agility.**

One of the conerns which has been raised during the work of the Group relates to whether or not there is an upper limit to agility, whether this be the airframe or any other system. This is perhaps most readily understood in terms of the airframe agility. Some of the upper limits are comparatively easy to describe, as they result from the limitations of the structure or rate at which controls move.

However, there are concerns that very high performance may be dangerous to use, as the more aggressive the use of the airframe, then the more the handling qualities may degrade. In very high workload situations, this may result in unsafe characteristics but the situation is likely to be difficult to quantify as it will depend on the aggressiveness of the pilot. If high performance is dangerous to use, then pilots will avoid using it, hence flying qualities can provide major restrictions on the agility of a particular airframe.

The concepts of quickness parameters are comparatively well developed for rotary wing vehicles, as exemplified by ADS33C. For fixed wing, the concept is still in its infancy, but it would appear to be well worthwhile developing as an analysis tool, particularly if the vehicle will have to demonstrate high levels of agility in its class. Flying qualities need to be considered in the early design process. The concept of an "agility factor" for this phase of work where the focus is on probability of mission success or failure combined with a mission task element method of analysis will assist in mission effectiveness trade studies.

7) **Airframe agility is designed in from the outset.**

Only in exceptional circumstances can it be added later, implying the basic design was not balanced properly.

Operational Agility concepts can and should be applied at the outset of the design process, starting even with the Operational Analysis work. The objective is to determine the correct design balance between airframe aspects, weapons and the onboard systems with a view to maximising the operational effectiveness at an affordable cost and to ensure that there is adequate growth potential in the aircraft to take it through its Service life.

Typically, combat aircraft have to remain in Service for around 20 to 25 years. During this time, the onboard systems can be upgraded many times, as the changing needs of the operational environments dictate. However, the airframe is much harder to make any fundamental changes to, implying that the flexibility has to be built in at the outset. Provided this is recognised early in the design process, before detail work starts, then it is more easily accommodated. Adding capability later is always more expensive, and may need major structural repair work.

8) **Rapid prototyping of crew stations is an agility enabler.**

Modern crew station design focusses on the tasks for the specific missions which are to be performed. The objective is to be more effective in an overall performance sense and to be able to respond to changes in the external environment more adeptly than at present. This requires an understanding as to how the crew interface with the systems in order that the appropriate displays of information, as opposed to data, can be implemented. The process can and should be used to decide which functions are to be automated, rather than what can be automated.

9) **Changing combat situations result in dynamic missile envelope conditions that press the ability of the mission systems to present up-to-date information.**

The key here is the need for the systems to display information, not data, but in a form that the pilot can readily relate to and with a speed that is commensurate with the changing situation. Under some circumstances, it may even be appropriate for the system to take action and then inform the crew that it has already dealt with a situation, for example in response to an external threat. Again, rapid prototyping alloyed to adequate simulation and evaluation will prove to be key enablers of such technology.

**10) Pilot-Vehicle Integration for the expanded flight envelopes provides a major challenge with regard to displays.**

When at high angles of attack, new forms of displays are required to ensure that awareness of the flight path vector is maintained. Recovery from high angle of attack manoeuvres, using $45^{o}$ or more is accompanied by the feeling that the aircraft is not reducing angle of attack initially. They appear to maintain AoA and reduce flight path angle. This places additional burden on developing means to inform the pilot as to what is happening, particularly if the correct things are taking place, but it does not feel natural.

**11) Integration of propulsion systems into agile airframes places special requirements on the propulsion unit and its integration into the design.**

Engine response times need improving for carefree handling. The goal should be to obtain maximum power on the same time as the pilot can achieve his desired AoA.

Thrust vectoring offers a powerful control effector. A careful cost/benefit analysis is required for each individual project study. It may not always be beneficial or necessary to include such technology to achieve the desired effectiveness. PST should not be considered if it drives the configuration such that it penalises the aircraft over the rest of its design flight envelope.

**12) The concept of Sub-system agility is immature.**

On the limited evidence available to the Working Group, the concept does appear to be valid and examples have been provided in the report. However, the concept requires the establishment of a suitable vocabulary and unification of existing work. The definitions derived by the Group could provide a basis for further work in this area, which would appear to offer a worthwhile reward in terms of the operational effectiveness enhancements that could result. The Group believes that this would be worthy of a workshop activity in order to progress the understanding and determine the way forward.

The Group's view is that the study of Operational Agility is in a similar situation to that seen by the Flying Qualities community some twenty years or more ago when faced with fly-by-wire, highly augmented airframes for the first time. Much remains to be accomplished before Operational Agility attains the same status as Flying Qualities currently has. However, the benefits which should accrue from better understanding of Operational Agility will encourage a rapid progression. In particular, when funds are resticted, it is essential that there is an adequate understanding of where funds are best targetted for any project. The Operational Agility methodology derived by the Group should be able to provide major assistance to making logical decisions.

## 6.3: Achievement with Respect to the Set Objectives:

At its outset, the Group was given a set of eight obectives to achieve, if possible, as described in the preface to the full report.

These objectives, or aims, and the achievements against each are as follows:-

**1) To provide definitions, which are universally acceptable, of the terminologies involved in agility.**

The Group has derived definitions that can be applied, which seem to make sense and which ought to prove to be universal in their application. Hopefully, provision of the appropriate terminology can help alleviate some of the differences which have arisen in the past.

**2) To collate the results of lessons learned from experiments on agility.**

Currently, many of the flight experiments are still ongoing and the Group has had limited access to the very latest information. We have been able to use information which has been published, together with whatever the members have been able to bring to the table. However, this objective has not been fulfilled completely, but only partially.

3) **To define metrics or figures of merit for use in design and evaluation.**

No new metrics have been defined by the Group, rather the existing metrics have been placed into a unifying framework, which should be applicable not only to the airframe, but also to the other systems and sub-systems which contribute to the Operational Agility or combat effectiveness of the Weapon System. This objective has been fulfilled to the best of our ability.

4) **To explore and document the theoretical foundations.**

The theoretical foundation for airframe agility has been explored and documented in Chapter 2.1 of the report.

5) **To explore the operational pay-off of balanced capabilities between the airframe, systems and weapons.**

A methodology for completing this investigation has been proposed, with examples showing how it might apply across a number of different systems. The need to undertake studies early in the design and development programme has been clearly enunciated as a key to providing an Operationally Agile Weapon System.

6) **To highlight any specialised aspects applicable to rotorcraft.**

In undertaking the work, the synergy that has evolved between fixed and rotary wing vehicles has been marked. We have seen that the two communities are tending to come together, although there will always be marked differences. These differences stem from the differing functions that the vehicles perform, and the implications that this has for the technologies involved. We have learned from each other. Specific lessons from each are included.

7) **To indicate possible means of evaluation in flight.**

Having established a methodology for dealing with Operational Agility, the report concludes with a Chapter on evaluation. Our realisation is that evaluation has to be part of the process from the design outset and is not purely a flight test function. Indeed, evaluation methodology may influence the design process considerably.

8) **To recommend areas for further research and development activities, including possible collaborative projects.**

A number of recommendations have evolved from the thinking of the Working Group which could and should lead to a range of collaborative activities involving AGARD.

*Summarising, the Group believes that it has met the objectives which were set for it, with the possible exception of item 2, relating to the lessons learned from experiments on agility. However, the scope of the activity which has resulted has taken us int a far wider realm than the original proposal envisaged. The major consequence of this is that a better perspective of the integrated airframe and systems has resulted.*

***It is our hope that this report will enable the reader to share that perspective.***

## Chapter 7: Recommendations

There are a number of recommendations which result from the studies of this Working Group. These are as follows:-

**1) The Mismatch of Missiles and Weapons with Airframes.**

There is need for some form of formal discussion relating to the mismatches in development of missiles, or weapons in general, and airframes. The Group believes that this could best be addressed by a Symposium to illustrate the current problems and identify possible ways forward. It is noted that such an activity could relate or be a part of the proposal for a Symposium on Weapon System Integration which has been raised within the Flight Mechanics Panel.

**2) The Need for a Database Relating to the Systems Use in Operations**

There is a need for data to be obtained from service which can be made available to the whole community involved in aircraft design, assessment and operation. The capability to provide the necessary information exists as does the ability to handle the database that results. The Group recommend that a new working group could usefully address the problem, with a view to providing the necessary database. This new group would need the services of experts in operational use, design, and information systems technology. The objective would be to recommend ways of achieving a database of use to all disciplines involved in the design and procurement of Operationally Agile aircraft.

**3) The Tactical Meaning of Agility Metrics needs to be Established**

Work needs to be undertaken to establish the tactical meaning of agility metric results, such that the value of Operational Agility studies can be quickly established and the resulting designs be shown to be more effective in a manner which fits the needs of the operators and purchasers.

**4) Additional Studies Required.**

Further studies are recommended in the following areas before a complete understanding of Operational Agility will be quantified:-

Sub-System agility concepts and the possible metrics need to be developed further with more examples of application of the proposed structure to test its fitness.

Develop more rotary wing metrics compatible with the Operational Agility structure, particularly for the airframe, which currently lags the work done in the fixed wing areas.

Develop a complete library of mission task elements which can be used in the development and assessment of Operational Agility for either fixed or rotary wing vehicles.

As the upper bounds on agility remain to be determined, there is a need to gather more quickness parameter data. At present, the quickness parameter concepts are used by the rotary w[illegible] community, but it would appear applicable and useful for fixed wing applications as well. It is recommended that further work be done on this concept for fixed wing application.

Further analysis of the relation of flying qualities and vehicle performance to define the upper limits on airframe agility is needed, particularly if aggressive use of the airframe causes the handling qualities to degrade. This requires dedicated evaluation tasks where both the objectives and success criteria are clearly defined.

Develop an "aggressiveness" rating system to parallel Cooper-Harper.

**5) Establish the Influences on Awareness of High Rate and Acceleration Manoeuvres.**

The effect of high angular and linear rates and accelerations under varying visual reference conditions needs to be established if agile airframes and displays with which the pilot can interface correctly are to be achieved. The concern here is that what might be perfectly acceptable under planned flight test conditions will be of little use or even dangerous when manoeuvring aggressively at maximum rate or rate of change of any flight condition, particularly in a dynamic combat environment. Use of high rate manoeuvres may be particularly dangerous under less that ideal visual conditions or when pilots are distracted by combat demands.

**6) Establish the Influence of Prolonged Exposure to Sustained 'g' at Moderate Levels.**

Determination of the relationship between sustained high 'g' below the level causing loss of conciousness and loss of situational awareness. This is a direct corollary of the previous recommendation.

**7) Revise the Way in Which Future Aircraft Specifications are Written.**

Specifications should be written to define the function to be achieved, from which the levels of performance can be derived in conjunction with the appropriate trade studies. Each new airframe project should be assessed in its own right to establish which technologies are affordable or relevant. Technology should not be included for its own sake. No one item should be inviolate, all items in the detail engineering specification should be tradeable to ensure the correct design balance results.

**8) Adopt Concurrent Engineering Methods.**

A concurrent engineering approach between customer and supplier will help to ensure that the necessary objectives are achieved.

# Appendix A Designing Helicopters for Agility

## 1 Introduction

Among all the missions selected for the modern combat helicopter, air combat looms as that which inspires the most uncertainty for the designer. Many of the designer's questions are centered in two areas of concern - the specific nature of helicopter air combat maneuvering and the nature of the combat world into which the helicopter will be thrust.

This Appendix is a version of a paper published by one of the authors a few years before the work of WG19 began, but is felt to be so germane to the subject that it is reproduced here in its entirety, with little editing. It is hoped that this personal view will shed some light on several areas of this vast landscape, and by doing so perhaps help define and clarify several points so that the work of designing the next generation of fighter helicopters can begin.

The Appendix is divided into two subparts, each discussing some important aspects of the above listed areas of concern, and each attempting to recommend some areas where additional research might prove beneficial in bounding the seemingly endless problem of designing for fitness in air combat. We discuss the nature of manoeuvrability and its limits, the capabilities of various aircraft in the low altitude air combat arena, and give some insights as to use of air combat VTOLS in land battle.

## 2 Helicopter Air Combat Manoeuvring

Any discussion of the nature of helicopter air combat maneuvering requires some definitions to help scope the areas of study and establish meaningful design responsibility.

Intuitively, the properties of the aircraft which support its ability to maneuver can be thought of as two distinctly different measurable functions, one relating to the degree to which an aircraft can be maneuvered, and another relating to the rapidity and precision with which the aircraft can be maneuvered. In Reference 1, we offered the below listed definitions, which are reviewed here.

Maneuverability - A measure of the ability to change the flight path velocity vector through a change in energy state. Typical measurable quantities of maneuverability might include the rate of climb, rate of turn, and the normal or longitudinal acceleration

Some typical design areas which influence maneuverability include specific excess power or thrust, the allowable load factor, and the existence of various limits imposed by a specific subsystem.

Agility - A measure of the ability to change the maneuver state rapidly and accurately. Agility is primarily a control function, encompassing the properties which permit quick, precise piloted control, and which enhance the stability of the system in its maneuver state. Typical measurable agility attributes are the time to change from one maneuver state to another, the workload required to maintain a precise maneuver task, and the precision with which the task is accomplished.

Typical design areas which influence agility are control system sensitivity, damping, and bandwidth, engine response, system short term stability, system dynamic stability, and control cross couplings.

Agility is very much a pilot in the loop property, and the net measure of agility must always assess the total piloted task performance.

### *Manoeuvrability*

Before we discuss the specific design impact of various maneuverability design options, we must first review the sources of energy which provide the power to change the total system energy state. In this analysis, we will see that the aircraft's maneuverability is defined in distinctly separate speed ranges, based upon the energy available to affect the maneuver. We will also show that the limitation to maneuver will fall into similar areas.

Steady maneuverability, as denoted by the ability to maintain a maneuver state indefinitely, is often predicted in the low speed range by the available specific excess power (P ). More fully discussed in Reference 1, we will simply

note here that at speeds above approximately .5 times the maximum level flight speed (VH) specific excess power may not be useful for predicting total maneuverability, since transient maneuverability levels can significantly exceed steady state values.

Transient maneuverability levels are enhanced through transfer of energy from potential or kinetic sources or through the use of temporary powerplant uprating. Considering the nature of helicopter maneuvers, it is common practice to use a 3 second period to define transient maneuverability, since a significant and useful flight path deviation can be made in approximately 3 seconds.

Figure 1 displays the specific energy available to a typical modern helicopter. Note that the energy available from specific excess power is also presented. This will help orient the reader as to the relative quantities of energy available to power any particular maneuver.

During air combat flight tests, deceleration rates of 15 to 20 knots per second were recorded in the H-60 and S-76, at speeds around 130 to 150 knots during decelerating turns. The recovery of kinetic energy during these maneuvers helped allow transient normal load factors of approximately 2.7 to 3.0 g. Of note also is the fact that these decelerating turns were flown with the aircraft in autorotation, where rotor speeds of 110% were attained and no significant engine power was being developed.

As shown in Figure 1, energy extraction of 20 knots per second at 120 knots requires a net rate of change in specified energy of approximately 200 feet per second. One can infer that such maneuvers will always result from kinetic energy conversion and not from altitude loss, since an altitude decay rate of 12000 feet per minute would be very unacceptable to helicopter pilots in terrain flight. Note that usable kinetic energy diminishes rapidly below approximately 60 knots, so that maneuverability will not be usefully improved through airspeed loss at low speed.

Transient maneuverability can be further enhanced by extraction of energy from other sources, such as rotor kinetic energy. For modern helicopters, approximately 100 feet of specific energy may be stored in the rotor, as shown in Figure 1. The depicted rotor specific energy assumes a rotor speed reduction from 125% to 90% of reference speed. Such rotor speed excursions are common in touchdown autorotations, and here are shown to provide the same energy contribution as about two seconds of equivalent excess engine power.

As Figure 1 infers, the available kinetic energy of the air vehicle dominates at speeds above about 120 knots. This would indicate that significant advantage can be had if greater speeds are held at the onset of battle. The airplane air combat axiom "speed is life" is derived from this relationship. As we will discuss later in this Appendix, the tactical benefits and penalties of speed in helicopter air combat are not so simply analyzed, and significant speed differences between adversaries has generally (perhaps paradoxically) shown that advantage goes to the slower aircraft, or the one which can decelerate more quickly.

Figure 2 shows the relationship between the measured Air-to-Air Combat Test II (Reference 2) data and the calculated Ps for the H-60, showing that Ps was a good predictor of maximum potential in the low speed areas, where transient maneuvers are inhibited due to insufficient kinetic energy.

The limits to transient normal load factor capability (Nz) at speeds above about .5 to .6 V is generally due to the onset of retreating blade stall on most modern designs. As higher rotor thrust is demanded, blade loading will increase and eventually reach unacceptable values, denoted by sharp changes in the blade pitching moment of the retreating side of the disk. If stall is allowed to progress too far beyond initial onset, cyclic control can be lost and a catastrophic flight condition can ensue. In some designs, the blade pitching moment can overpower the cyclic control hydraulic system and in turn feed back powerful rotor forces to the cockpit. Such events have been experienced in the AH-1S and Aerospatiale 365N during air combat trials, and are sometimes described as "Jack stall".

The limits of typical designs can be estimated through analyzing the aerodynamic blade loading ($CT/\sigma$), as illustrated in Figure 3. A more complete discussion of the limits and impact of $CT/\sigma$ on maneuverability is presented in Reference 3 and an excellent topic of discussion of the design concepts are presented in Reference 5. For the purposes of this discussion, the most significant concern to the designer is the impact of rotor solidity to the maneuverability of the design. As can be seen on Figure 3, the ratio of the design level flight $CT/\sigma$ to the maximum $CT/\sigma$ determines the limits of transient normal acceleration. Since $CT/\sigma$ drives many other design attributes, such as rotor system weight and hover figure of merit, compromises between maximum maneuverability

and optimum hover payload are often made. For most single rotor, tandems and tilt rotor designs, the maximum demonstrated $CT/\sigma$ is about 0.2. For the Rigid Coaxial Sikorsky Advancing Blade Concept Helicopter (ABC), the maximum demonstrated $CT/\sigma$ is about .28. These values are used in the calculation of Figure 3 relationships.

Typical design trades are illustrated in the design of transport tilt rotors, where high design $CT/\sigma$ is used to achieve excellent figure of merit, reduction of rotor system weight and higher payload fractions. The limited helicopter mode maneuverability of the XV-15, with a design aerodynamic blade loading of .125, is shown in Reference 6, where the program maximum helicopter mode Nz of 1.3 g is published. (The design $CT/\sigma$ of the MV-22 is .155.)

Once wingborne, of course, the tilt rotor shows excellent load factor capability and the designer may choose a wing loading to optimize mid or high speed maneuverability. The penalties of vertical drag and wing structural weight may limit the attainment of helicopter levels of low speed maneuverability for practical tilt rotor designs.

For the helicopter, winged configurations or auxiliary thrusters may extend the aerodynamic blade loading curve to much higher advance ratios, since the available rotor thrust can be more fully devoted to maneuvering requirements. Again, Reference 5 discusses these concepts.

For coaxial helicopter designs, retreating blade stall has different implications on high speed maneuvering. Since the counter rotating systems have an advancing blade on each side of the aircraft, it is quite possible to transcend the retreating blade stall region while retaining excellent control power. For the Sikorsky ABC rotorcraft, extremely high aerodynamic blade loadings were achieved during flight test, as discussed in Reference 7 and shown in Figure 4. These data indicate that an ABC rotorcraft possesses a unique combination of low and high speed maneuverability, and represents a viable air combat VSTOL candidate.

Care must be taken not to infer such high load factor properties for all coaxial designs, however. Since the ABC is a high offset rigid rotor design, blade pitching moment changes do not induce flapping changes, and rotor clearance between the two disks is retained. Articulated coaxial designs may not retain such blade clearance, and therefore may not posses improved high speed load factor properties.

Considerable work remains to be performed to understand the benefits of less conventional maneuvering means. The helicopter is particularly endowed with omni-directional controls, so that enhanced yaw maneuvering may be designed into the aircraft for comparatively small penalties.

Several studies have indicated that the yaw degree of freedom offers fertile ground for significantly decreasing time to point during engagement. While rotation about the yaw axis may be considered a pure agility function, it appears that the benefits of yaw pointing is to some degree due to the side force generated by the fuselage during side slip maneuvers. This side force is directed toward the desired turn and is reduced in conjunction with the normal load factor, so that a considerable increase in turn rate can be used. The report of the U.S. Army Aviation Applied Technology Directorate (AATD) sponsored program conducted by Sikorsky Aircraft, 'Helicopter Maneuverability and Agility Design Sensitivity Study" (Reference 8), provides a full discussion of these effects.

Figure 5 illustrates the relative improvement in the turn time for a baseline helicopter design when a number of design attributes are varied. Note that use of 11 deg of sideslip proved as valuable as the addition of 13% more horsepower, and that 24 deg of sideslip reduced the baseline turn time by nearly 20%. It is possible that sideslip angles of over 60 deg could be used to even further enhance this maneuver.

An air combat simulation study (Reference 9) also explored these issues and concluded that, in part, "Though the degree of sideslip used by individual pilots varied, the most successful pilots used aircraft sideslip performance to significant advantage. For these pilots, the sideslip envelope typical of early attack helicopters is clearly not sufficiently large. The envelope afforded by modern utility aircraft is close to adequate if the entire envelope can be exploited without consequence. If the assumed ability of fire control computers to compensate for sideslip velocities is correct, the skilful use of sideslip for weapon pointing is a distinct tactical advantage."

Yaw maneuvers at higher speeds have additional benefits. The large increase in drag induced by the sideslip improves the deceleration of the aircraft, thereby allowing quicker transition to the best maneuvering speed regime. This deceleration, coupled with the increased centripetal acceleration available to aid the turn rate, offers significant advantages in reducing turn times in forward flight.

The limits to use of sideslip at forward flight is generally due to structural constraints on the tail rotor or its support structure. For coaxial or NOTAR designs, since only tail cone structural loads must be considered, allowable sideslips may be greatly increased. Use of a rudder on coaxial or NOTAR designs may prove very beneficial.

Similar off axis pointing virtues are discussed in Reference 6, where the increased targeting available from pitch pointing are discussed. Auxiliary propulsion also deserves some attention, not only for its ability to provide direct axial acceleration or deceleration, but also because it permits helicopters to pitch point in a manner similar to tilt rotors.

## *Agility*

Agility is the principal domain of the handling qualities engineer, but the important aspects of agility pervade the modern helicopter design. For example, the required bandwidth and damping of an air combat helicopter will probably dictate the rotor head flapping hinge offset, thus setting a very important cornerstone for the helicopter design. In a similar manner, the response of the engine determines the precision of rotor speed retention, and thereby determines to an extent the short term, small angle, dynamic stability of the aircraft.

Designing for high levels of agility has some inherent pitfalls. If, for example, a high offset rotor is needed to provide the bandwidth required for precise, highly damped control, the inherent cross couplings of that rotor may not be desirable and may negate the favorable attributes which initially selected the rotor design.

Considerable past work has set the ground work for agility requirements. Notably, References 10 and 11 provided the data shown in Figure 6 which displays the roll damping/sensitivity relationships desirable for acceptable nap of the earth attack helicopters. These results indicate the need for quick, highly damped response to controls, but the results are based on tasks that only partially reflect these typical of air-to-air combat.

A comprehensive document encompassing a great deal of effort in the field is the new "Proposed Specification for Handling qualities of Military Rotorcraft", (Ref. 12). Here we see requirements which attempt to specify the true nature of the control task through bandwidth, time constant and rate/amplitude ratios. Certainly, while the absolute values must be carefully verified in a range of flight tests, the methods of depicting and quantifying required characteristics appears excellent. While we in industry express a few reservations about the absolute values required (some appear too lax, some too stringent), we believe the basic document to be a large step toward accurately quantifying the needed handling qualities of the helicopter.

Many factors influence the agility of the aircraft when in the pilot's hands. The complex nature of typical air combat tasks and precision pointing maneuvers make it difficult to examine only one axis at a time, because the command of high rates and rapid settling on target often require considerable multi-axis workload. To a great extent, a quasi-single axis analysis will not suffice, unless great care is taken to define the limits of acceptable cross axis coupling.

The recently completed adaptive fuel control flight test program demonstrated the differences between a conventional hydrodynamic fuel control and an isochronous adaptive digital control. The tests, conducted under contract with the U.S. Army AATD, have produced an interesting set of data relating the influence of transient rotor rpm ($N_R$) changes to the handling qualities of an S-76 helicopter during precision targeting tasks. A laser gun simulator system was used to quantify the pointing precision of the aircraft during a number of air-to-ground and air to-air attack maneuvers. The data indicate that the fine scale pointing capability of the aircraft (typically within 5 to 20 mils) is strongly influenced by the rotor speed stability of the engine fuel control Typical data is shown in Figure 7 to document the change.

The effect of $N_R$ (rotorspeed) stability on handling qualities has always been an area of prime importance to the pilot. Small excursions in $N_R$ (+1 to 2%) produce fairly large changes in the control trim of the aircraft, since most of the forces and moments change by the square of the $N_R$ change. This is especially true in yaw, where engine torque transient lags and $N_R$ changes strongly upset anti-torque balance, and ensuing sideslip perturbations disturb all axes.

These results clearly illustrate the complex nature of agility and further show how important is the need to reduce cross axis coupling as much as possible. While Reference 12 allows rate coupling ratios of .25 for pointing

tasks, we believe that these values are considerably beyond tolerance and that the mission requirement may be more in the order of 0.025 to 0.1.

Sikorsky experience has shown that VTOL designs with little or no short term cross coupling are likely to perform well in the typical high bandwidth, high workload targeting tasks. Shillings, in reference 6, makes note of the relatively decoupled nature of the typical tilt rotor design, and Zincone in reference 7 discuss this feature of the ABC coaxial helicopter configuration. It is likely that a design with high bandwidth, highly orthogonal pitch, roll and yaw control characteristics will prove more effective in air combat.

The data also indicate that the higher bandwidth of the high offset main rotor design ABC, in conjunction with its inherently lower moments of inertia, especially in roll and yaw, may show it to be a superior air combat configuration.

Many of the tests performed during the Adaptive Fuel Control program were geared toward the desire to produce mission effectiveness derivatives for the variables under examination. We believe that this method of measuring handling qualities by mission effectiveness testing is essential to truly quantifying the benefits of various attributes. Through the use of the gun simulator, we were able to quantify the natural dynamic stability and piloted targeting changes with a great deal of confidence. The data were reduced in a manner so that a program decision could be made on the basis of firm data supporting the trade between effectiveness and system cost, weight or reliability. As shown in Figure 8, the change in targeting accuracy induced by the adoptive fuel control can be directly related to an increase in the number of stored hits in the system. In the hands of a design analyst, the increased cost and weight of an adaptive fuel control can be balanced against the lesser number of rounds that need be carried (or the greater numbers of kills available for the same weapons load), once the required targeting accuracy is known. For the data shown, if target accuracies of 10 mils are required for the weapons system, the adaptive fuel control equipped aircraft proved to be equivalent to 1.18 conventional aircraft.

While we support the traditional Cooper-Harper Rating System discussed in reference 13, we believe that modern technology has permitted us to more carefully quantify not only the precise output effectiveness of the piloted system, as discussed above, but also the pilot's control activity performed in pursuit of the task. The cockpit stick activ :y recorded during each data run in the adaptive fuel control flight test program was analyzed to establish workload differences as the fuel control properties were changed. Using integrated stick crossings about a running mean, the stick motion workload data matched the mission effectiveness data quite well, and supported the overall test conclusions.

In short, we believe that the complex nature of combat aircraft agility requires us to carefully define precision tasks, measure the task performance accurately and to high bandwidth, and to measure the pilot's activities to clearly quantify his or her efforts. With these requirements met, the previously difficult job of clearly quantifying what the pilot really prefers appears within reach.

To further support the need to accurately quantify the piloted task, we carefully standardized the maneuver entry conditions and relative target position so that gross maneuver time (time from entry to target acquisition) could be measured (Figure 9). We also recorded and plotted typical maneuver data, such as load factor, aircraft attitudes and rates. In this way, we attempted to define the appropriate aspects of the maneuver so that data reduction could reveal any pertinent differences induced by the configuration change. We found that only by quantifying gross task time, degree of maneuver aggressiveness, pilot workload and pointing accuracy could we repeatedly identify the changes due to configuration. For example, some of the subject pilots would use the increased agility of a configuration to achieve a more aggressive gross task and thereby reduce the task time. In doing so, this pilot might very well sacrifice precise pointing to some degree by entering the acquisition cone of the target at much higher angular rates. By having carefully standardized the entry conditions, the net maneuver time was shown to have been reduced in such cases.

Using the test methods now available to quantify some formerly illusive data, we believe many areas need further study. Examples include:

Careful flight test validation of some critical areas of the new proposed handling qualities specification (Reference 12) especially the cross axis coupling criteria and the small angle rate/amplitude ratios, especially in pitch and yaw.

i) Careful flight test examination of control laws optimized for air combat.

ii) The integration of flight controls and fire control systems, so that targeting systems exercise some ability to point the parent aircraft. How much authority, through what laws and with what crew interface are key questions to be answered (recent work at Sikorsky has demonstrated the potential of integrated fire and flight control systems in helicopters - Ref 19).

iii) The electronic enhancement of agility, through feed forward gain shaping, promises considerable pay-off through reduction in mechanical rotor hinge offset. How much enhancement is available, at what penalties? Pilots believe that natural feedback stability limits will show strong disadvantages for high degrees of feed forward, but perhaps only precise targeting data will provide the answer.

iv) Self-protection of the airframe and subsystems from pilot abuse during critical air combat tasks is mandatory for future designs. The U.S. Army Research Technology Laboratory sponsored Helicopter Maneuver Envelope Enhancement Study, (HELMEE) ongoing at the time of writing, is attempting to explore these issues. Continued simulation and the flight test is surely warranted.

More work on piloted agility enhancement is justified because the payoff for agility improvement is impressive. As shown in Figure 5, the net time to turn 90 deg is as strongly influenced by agility as it is by maneuverability, and at far less weight impact for the overall vehicle. With such benefits available, the design team must strongly weight the inputs from the handling qualities engineer.

## 3 The Nature of the Helicopter Air Combat Battle

To understand how future air battles between helicopters will be fought, we must understand how they can survive at all on the modern battlefield. We must then recognize that helicopter air combat will be one of several concurrent battle scenarios fought in conjunction with, and in support of, a land battle between enemy forces. The nature of the combined arms battlefield and the terrain and environmental conditions will dictate the specific tactics which must be employed.

One comment must be made concerning the perception of how technology drives the battle. It has been asserted that VTOL speed capability is the newest technology breakthrough, and through its exploitation, significant combat advantage can be gained. While we support the contention that vehicles with higher speed potential are able to be used more productively and more flexibly on the modern battlefield, since the increased speed can serve as a multiplier in some scenarios, we must not begin the blind pursuit of speed, while possibly sacrificing virtues which are shown to be required for survival in close combat.

Our studies show that the control of detection, and the element of surprise, are dominant in many air combat scenarios and that the use of low signatures, nap of the earth (NOE) tactics and superior sensors far outweigh the importance of speed alone. In short, the key technology we have identified is the current inability of ground and air systems to locate aircraft is the NOE environment.

Our main concern with VTOL speed is that current VTOL designs trade low speed maneuverability, agility and signatures for significant increases in dash speed capability. Since these low speed properties are those which support survival and effectiveness in combat, we are left with an apparent paradox where designing for higher speeds may significantly degrade the combat performance of the VTOL.

The author's paper "Cockpit Concepts for Nap of the Earth Helicopters" (Reference 14), discusses the relationships of speed, height and detectability, based upon both flight test and analytical data. From this data, we conclude that the low detectability of the NOE helicopter presents a significant advantage in combat. Our Ft. Campbell flight test data, shown in Figure 10, illustrates that higher speed (hence higher height) significantly increases detection distance and thereby degrades survivability.

A number of sources have asserted that increased speed decreases the exposure time and offers a significant survivability advantage. We believe the data refutes this for typical low subsonic terrain flight. Note that the exposed distance increases with speed, and the area of exposure increases by the square of the exposure distance. We can, therefore, infer that for a random threat lay down, the number of exposed threats is vastly increased with higher speed, offsetting the effects of reduced exposure time, which falls linearly with increased speed.

While we can expect active and passive sensors on air defense systems and air combat helicopters to improve with time, these improvements may only complicate, not clarify, the NOE battlefield. The potential for jamming, anti-radiation weapons and deception will introduce new tactics and counter systems, but will probably only increase the need for terrain flight profiles to enhance survival.

In any case, we believe that helicopter air battles will not involve the protracted maneuvering for firing position seen in fixed wing air battles. The relatively close ranges of detection, a large percentage of which will be inside weapons range, will probably dictate a fast turn and shoot scenario. Figure 11 illustrates the differences between fixed wing and helicopter air battle. This chart, prepared by the author in 1985 and presented on a number of occasions, has been published in Reference 15.

Aside from their significant contribution to successful NOE flight, maneuverability and agility can serve as the decisive edge in mutually detected air combat, where clear line of sight at short range exposes the adversaries jointly. Here, the ability to turn and shoot will dominate, and agility and maneuverability enhances both offensive and defensive capabilities. It is also possible that in close battle, short, quick maneuvers to dash and descend for cover may help in defense against surprise encounters. During such close encounters, load factor, turn rate and turn radius capabilities help determine relative fitness.

The typical transient maneuverability of several designs is shown in Figure 12. The helicopter shown is typical of BLACK HAWK/Apache levels, the tilt rotor reflects the capabilities of the XV-15 and V-22, and the "Copter Killer" airplane shows the speculated capabilities of that possible configuration. For simplicity of discussion, agility effects are not presented. We believe that significant agility differences exist between the configurations presented, but that these differences support the conclusions drawn from steady maneuvering analysis.

When the load factor capabilities are translated into available turn rates, one can infer how quickly the various designs can bring weapons to bear on an opponent. Figure 13 shows these turn rate values and illustrates the advantage possessed by a typical modern helicopter at speeds below about 110 knots. Since these designs can decelerate quickly, even when battle initiates at higher speeds the helicopter can rapidly assume turn rate dominance

Turn radius also drives the problem, and in conjunction with the helicopter's initial detectability advantage, shows the disadvantage of a "copter killer" airplane design with equivalent turn rate but at higher speeds. Figure 14 illustrates this effect. Note that at equal turn rates, the lesser turn radius of the helicopter allows quicker weapons alignment and earlier success.

With this brief framework of maneuvering concepts, and an understanding of the nature of NOE tactics, some basic conclusions about future VTOL air combat can be drawn, and the properties of a good VTOL fighter can be defined.

**a) Detection** will drive the battle. The side with first detection will control the engagement and with adequate systems and numbers will probably win.

Detection in NOE is problematic. Because active sensors degrade signatures, perhaps unacceptably, passive sensing may serve as the best initial detector. Active sensing can be useful if the emitter is sacrificial or well protected. Use of combined infantry/aircraft teams may prove helpful.

NOE tactics may make precise detection available only when clear line of sight conditions exist, so that visual and electric sensing may be had simultaneously.

Aircraft attributes which support this critical phase of the engagement include:

i) Low inherent signatures including radar, IR, acoustic and visual.

ii) Good maneuverability and agility to permit flight close to terrain and vegetation without undue pilot workload and with high confidence.

iii) Small size to permit selection of small NOE lane widths and allow masking behind or below small features.

vi) Low disk loading/downwash to produce as little disturbance to the natural vegetation and ground cover.

**b) Engagement** With appropriate attention to the above factors, the initial engagement will probably occur upon a relatively surprised enemy, permitting ambush type engagements similar to typical armor and infantry engagements. First detections will probably fall well inside weapons ranges, so that weapons systems which permit quick shots will be important. Use of combined arms fire support will be crucial, especially where numerical superiority cannot be assured.

Aircraft System attributes which support the initial engagement include:

i) Visionics and avionics which support close earth sensing, detection and engagement in a variety of environmental conditions. The display systems used to provide the pilot with situational information under non-visual conditions (night, reduced visibility, etc.) will probably serve as the principal limit to the below listed attributes. With the requirement for night air battle, such systems can serve as the key discriminator. Wide field of view, helmet mounted displays with imbedded heads up information are highly enhancing. Such displays may serve, along with the tactical systems mentioned below, as a force multiplier due to the vast increase in effectiveness they potentially provide.

ii) Fire control systems which permit rapid target identification, weapons alignment and fire/launch.

iii) A suite of weapons to permit engagement of a variety of ranges, and with overlap of engagement ranges to permit high probability of kill. At the very least, a high rate large caliber gun and a fire and forget missile must be had. A superior air fighter will probably have a turreted gun for off axis engagements and two missile types, the second type to permit engagement of high altitude, longer range threats. High agility and maneuverability to permit rapid alignment of weapons and sensors and to support fire and maneuver tactics. After initial shots, aircraft will probably move to new firing positions to exploit the situation after threat reaction. The ability to fire while maneuvering, especially accelerating, will be enhancing.

iv) Tactical systems which orient all flight members to the positions of all friendlies and threats and which allow the quick coordination of combined arms fires will serve as a force multiplier, allowing optimum use of all committed aircraft. With such systems, the battle captain can rapidly reposition his aircraft for maximum effect.

v) Ballistic tolerance to permit continued effectiveness after hit.

**c) Post Engagement** Sustaining military power in the assigned area requires other attributes which support the ability to re-group, re-deploy and re-engage. The flexibility of the fighting force is to a great degree driven by the properties of the aircraft it uses.

i) The air combat VTOL must be lined to the Air Defense network, both as a shooter and as a sensor. While it is not advisable to burden all of the air combat VTOLs with full air defense sensing, some members of the squadron may be chosen for partial offload of offensive systems and weapons and installation of a more sophisticated sensor suite. Such aircraft can serve as mobile SAM sites, if the excess power available for normal maneuvering were partially sacrificed for extra sensor and weapons load.

ii) Time on station, derived through sufficient fuel and efficient use of that fuel, will permit long sustained overwatch in protection of anti tank and transport helicopters or as pickets at the flanks of the battlefield.

iii) Dash/cruise speed sufficient to permit rapid movement across uncontested portions of the battlefield. While high speed during engagement is probably a severe handicap, the ability to cover large areas for rapid reaction or recovery is certainly enhancing. The dimensions of the required area of operation, along with the response time provided by the Air Defense network will dictate the speed requirements. However determined, the speed requirement must not degrade the low speed signatures, maneuverability or agility.

iv) High enough reliability to permit long missions with many engagements between mission aborts.

v) Fast turnaround time for fuel and weapons upload. With combined flights comprised of transport helicopter and air combat VTOLs, a rapidly deployed forward area rearm point could be set up to permit quick uploads and further multiply the force.

vi) Sufficient numbers on the battlefield to permit reasonable parity in most engagements.

Some excellent discussions of tactical employment are provided in references 16, 17 and 18. Major Gen Cannet's article, reference 16, shows the thinking of an army officer and deftly describes the world of helicopter air combat in the context of land battle.

To make careful trades during the initial design phase, the design team must rely on various analytical tools to determine the most effective combination of attributes. Unfortunately, the NOE combat world presents a very complex and challenging task to the analyst.

The detail of the terrain base must closely match the size of the helicopter, so that careful intervisibility calculations can support detectability and survivability trades. The rules which apply to battlefield conduct of the NOE helicopter must be understood and applied in battle simulation. Accurate representations of flight profiles, speed and altitude relationships and threat sensor performance in clutter must be input so that realistic answers are obtained. At this time, there is great need for improvement in all these areas. Until substantial effort is expended to obtain and apply this information, the unchallenged use of computer models may lead to seriously underpredicting the combat capabilities of NOE aircraft.

## 4 Conclusions

1. Maneuverability is a key air combat attribute and is driven by available rotor thrust and excess power. The configuration selected will determine the relationship between maneuverability and speed, especially in the trade off between dash speeds above 200 knots and acceptable low speed maneuverability.

2. Agility is a key air combat attribute, and is driven by bandwidth, control power and low cross axis coupling. Agility can be significantly affected by a number of aircraft and system attributes.

3. Unorthodox maneuver techniques, such as enhanced sideslip, auxiliary thrust and pitch pointing could be more fully exploited to permit higher combat effectiveness without adverse impact on other design requirements.

4. The advancing blade concept coaxial helicopter configuration (ABC) shows particular capabilities as an air combat aircraft. High maneuverability at low and high speed, high agility, and a potential for extreme yaw maneuverability enhance its adaptability as an air combat aircraft.

5. The introduction of an adaptive fuel control on one production helicopter produced a dramatic increase in targeting effectiveness. Similar improvements may be likely on other aircraft.

6. Mission effectiveness testing and precise piloted workload analysis techniques can significantly improve our understanding of the trades we must make in designing for air combat.

7. Several programs for additional flight testing of air combat attributes are recommended, including validation of requirements, determination of control laws, integration of fire controls, enhancement of agility, and self protection of the aircraft from pilot abuse.

8. Control of detection is critical to air combat success and serves as the principal difference between helicopter and fixed wing air combat. Additionally, increasing speed increases detectability and reduces survivability in terrain flight.

9. Modern helicopters possess maneuverability advantages over existing tilt rotors and optimized airplanes in terrain flight air combat.

10. NOE combat models require improvements in the areas of terrain detail, piloting path selection rules, speed and altitude relationships and sensor performance in clutter.

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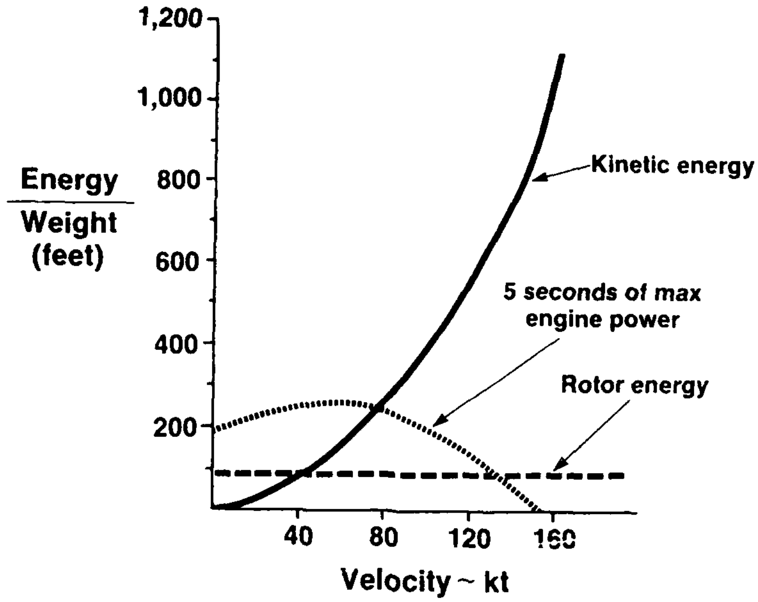


Figure 1. Energy Contribution to Maneuverability

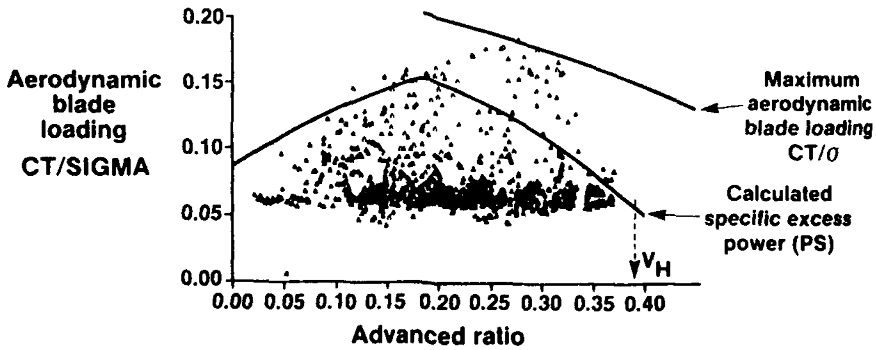


Figure 2. CT/σ Versus Advance Ratio

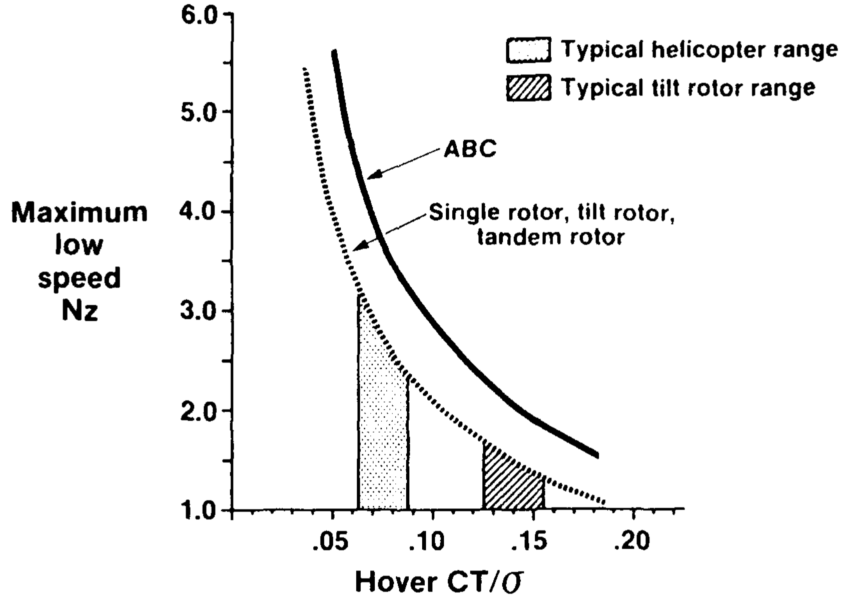


Figure 3. Design CT/σ Versus Low Speed Nz

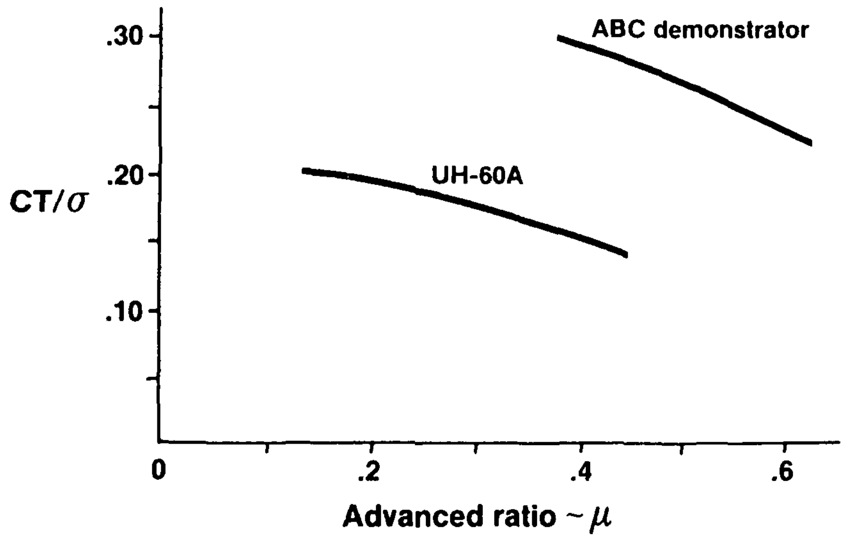


Figure 4. Maximum Demonstrated CT/σ

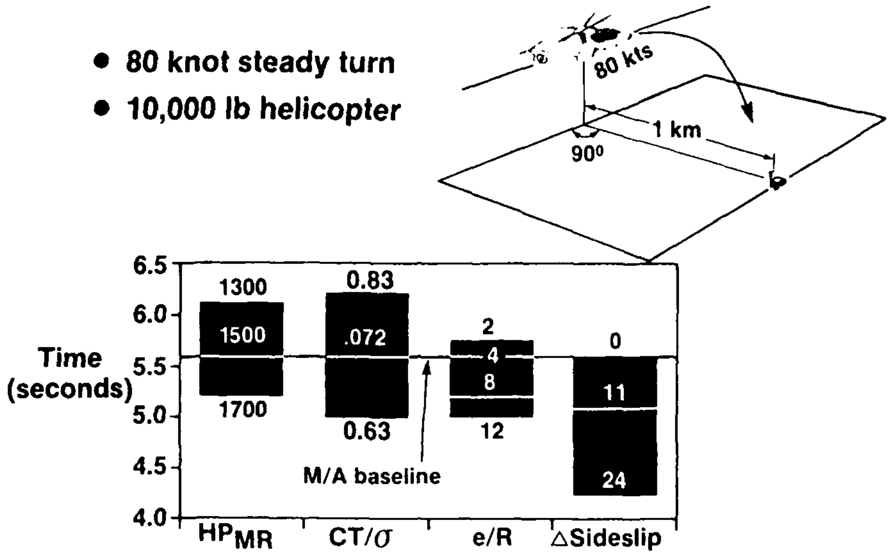


Figure 5. Design Impact on Time to Turn

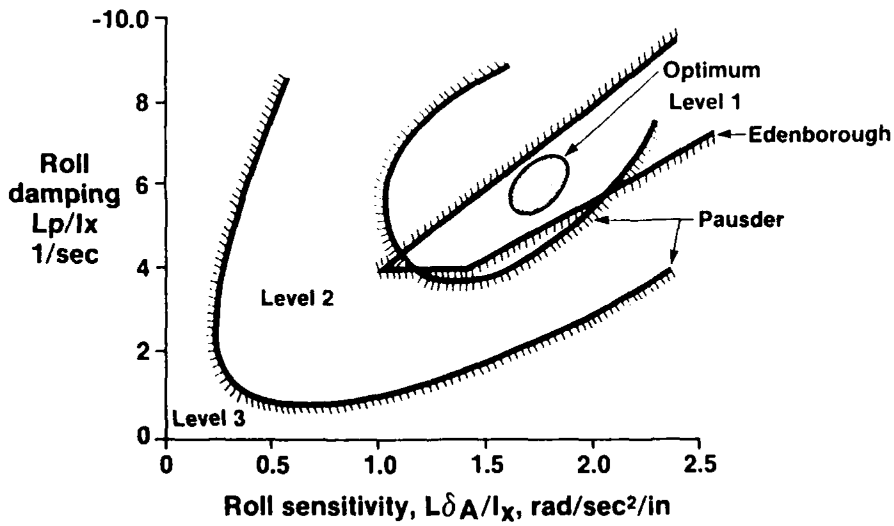


Figure 6. Attack Helicopter Recommended Roll Values

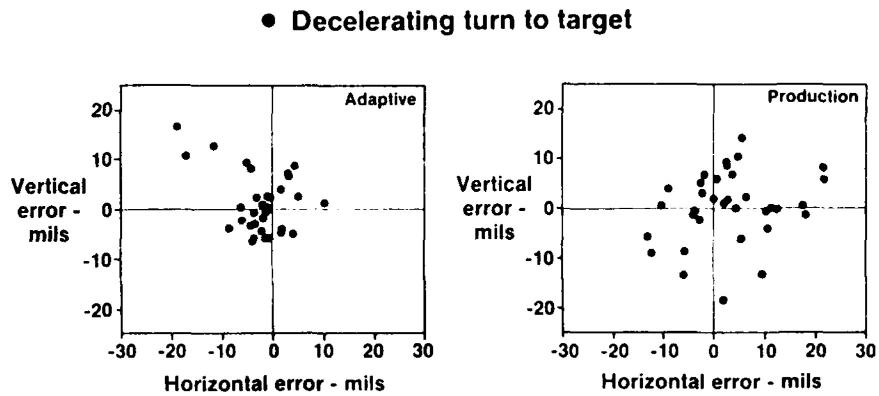


Figure 7. Engine Response Affects Agility

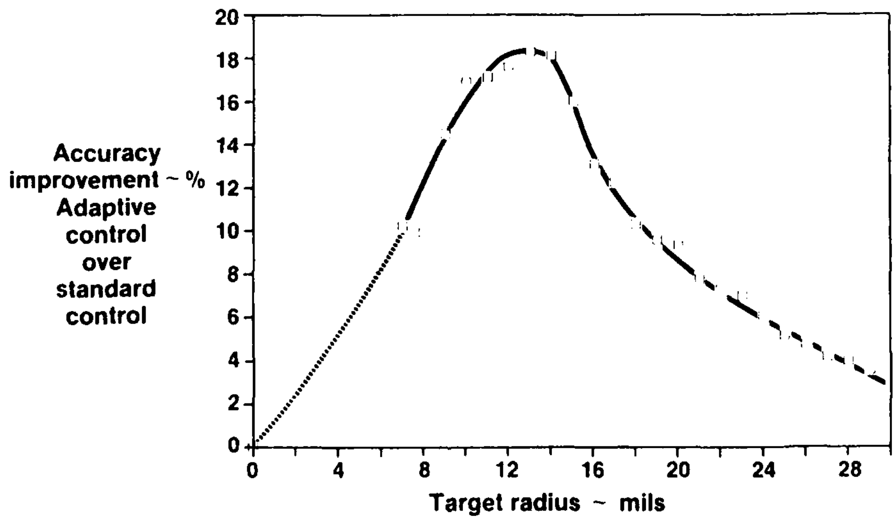


Figure 8. Accuracy Improvement vs Target Size

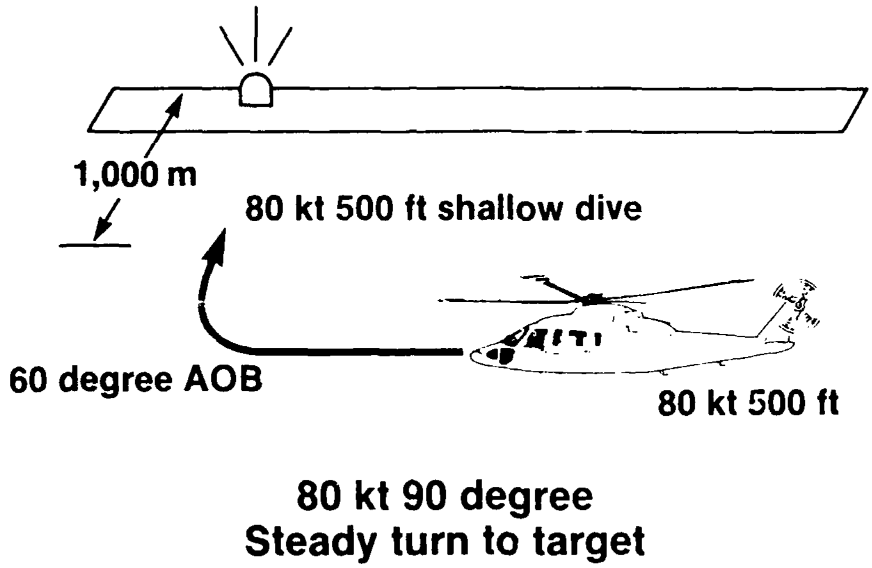


Figure 9. Sample of Standardized Targeting Maneuvers

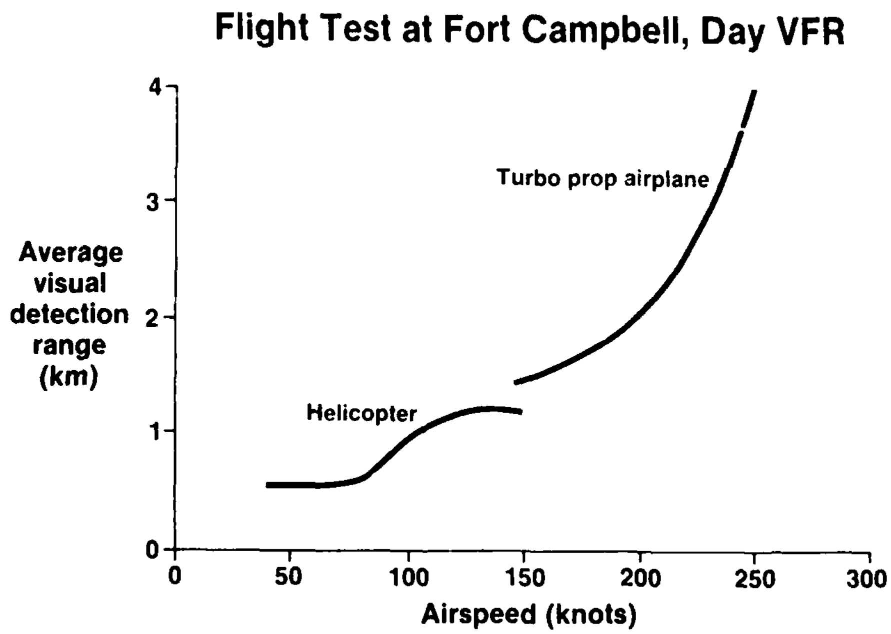


Figure 10. Speed Determines Height and Detection Range

| | Fixed Wing - High Altitude | Helicopter - NOE |
|---|---|---|
| • Detection | • Occurs at long ranges<br>• Environment uncluttered<br>• Speed does not alter detectability<br>• Detection ranges are significntly greater than weapons ranges | • Occurs at short ranges<br>• Environment very cluttered, EO/radar may not be usable<br>• Speed increases altitude, significantly increasing exposure<br>• Weapons ranges are greater than detection range |
| • Acquisition | • Maneuvers involve speed to jockey for firing position<br>• Speed dictates long time turns<br>• Weapons have limited Azmuthal capability, dictating aircraft pointing for weapons launch | • Given comparable weapons, the first one to shoot will win<br>• Rapid turns and quick shots will dominate<br>• Turreted guns permit off axis short range engagement |
| • Tactical Maneuvers | • Turn rate of 15°/sec to 20°/sec are maximum<br>• Turn Radii of 1/2 mile are minimum<br>• Considerable vertical manuevering is desirable | • Turn rates of 40°/sec to 60°/sec are maximum<br>• Turn radii of 100 feet are common-hover turns will be important<br>• Vertical maneuvering above NOE may not be permitted due to anti aircraft threats |

Figure 11. Differences Between Helicopter and Fixed Wing Air Combat

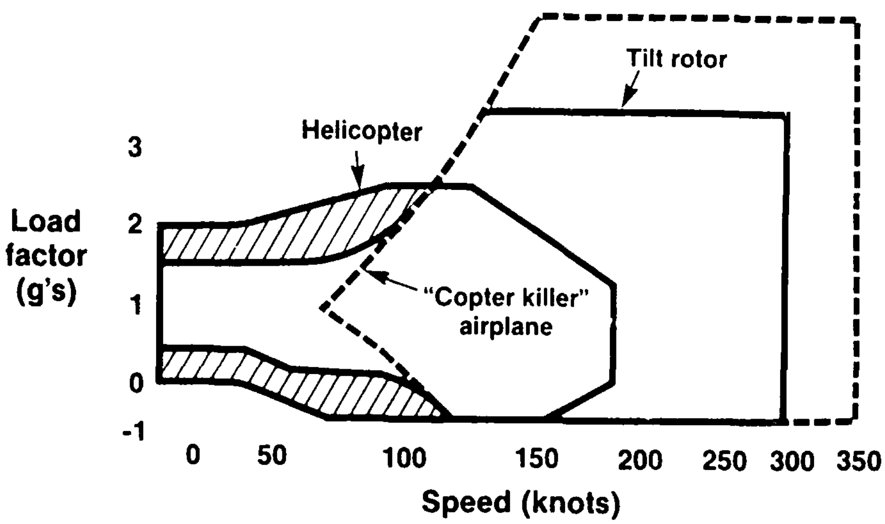


Figure 12. Maneuverability of Various Configurations

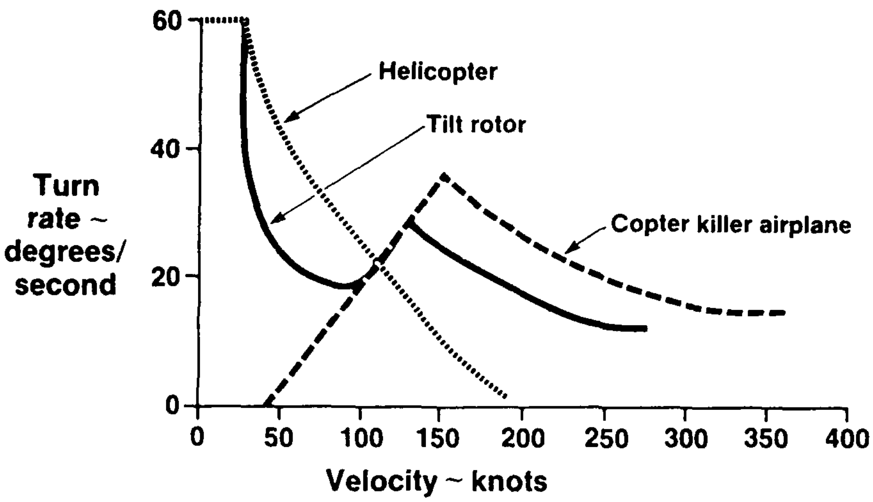


Figure 13. Turn Rates for various Configurations

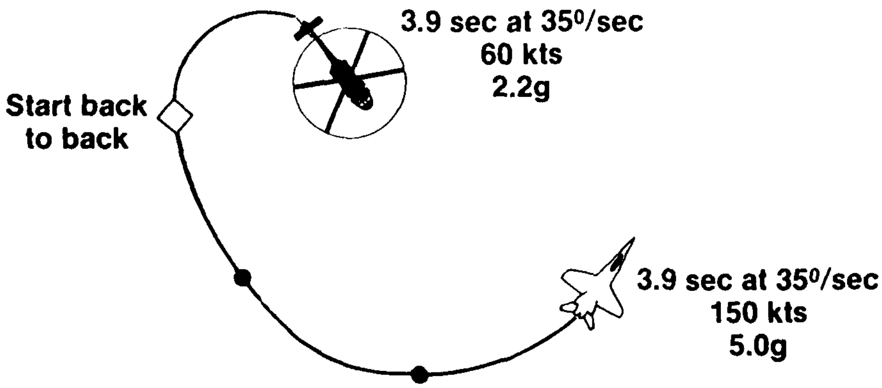


Figure 14. Smaller Turn Radius Points Faster

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| Fighter aircraft | Active control |
| Helicopters | Flight control |
| Air force operations | Terminology |
| Weapon Systems | |

**14. Abstract**


From previous AGARD activities, it was recognised that flying qualities and traditional aircraft performance parameters did not characterise the capability or effectiveness of combat aircraft, although they do offer a guide. Other expert groups had reached a similar conclusion. The subject that arose from these realisations was "agility". Recognising that this was an incomplete or immature concept and that a wide variety of sometimes disparate views existed, the Flight Mechanics Panel formed a further Working Group, WG 19, consisting of specialists from AGARD member countries, to study the subject under the title of "Operational Agility".

Working sessions were held at places of special interest to the group, between 1991 and 1993.

The specific aims of the Working Group were to provide definitions, which are universally acceptable, of the terminologies involved in agility; to collate the results of lessons learned from experiments on agility; to define metrics or figures of merit for use in design and evaluation; to explore and document the theoretical foundations; to explore the operational pay-off of balanced capabilities between the airframe, systems and weapons; to highlight any specialised aspects applicable to rotorcraft; to indicate possible means of evaluation in flight; to recommend areas for further research and development activities, including possible collaborative projects.

The Group has completed its study of Operational Agility with this report. In undertaking the study, a greater understanding has been reached of those subjects which influence Operational Agility and how these subjects, via the use of Operational Agility concepts, may be related to the combat effectiveness of the Weapon Systems. In reaching this understanding, the Group has proposed definitions of the agility terminology which should prove universally acceptable, has arrived at the methodology for assessment of the various component systems which contribute to the Operational Agility or combat effectiveness of a Weapon System, and has listed a number of major conclusions and recommendations.

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